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Hydraulic System Noise Study

annual report, section 3

Oklahoma State University

SEPTEMBER 1972

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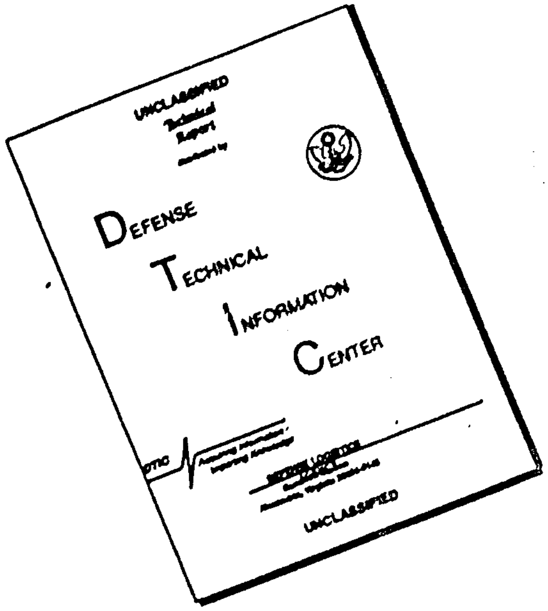

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HYDRAULIC SYSTEM NOISE STUDY (U)

SECTION III

ANNUAL REPORT

PREPARED BY

FLUID POWER PERSONNEL

NOVEMBER, 1972

U.S. ARMY MOBILITY EQUIPMENT RESEARCH
AND DEVELOPMENT CENTER

CONTRACT NOS. DAAK02-71-0074
AND DAAK02-72-C-0172

FLUID POWER RESEARCH CENTER
OKLAHOMA STATE UNIVERSITY
STILLWATER, OKLAHOMA 74074

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13. ABSTRACT

The purpose of the OSU-MERDC Hydraulic Specification Program is to develop industrially acceptable test procedures and requirement specifications relative to the performance of hydraulic components and systems to facilitate the military's "buy commercial" approach. Although the program has been aimed toward components and systems for future 3000 psi operating pressure levels, it was intended that the test procedures be applicable to any pressure level.

This report presents a detailed account of the experimental verification part of the hydraulic noise study. Test procedures for hydraulic component noise, developed under this contract, are presented and experimentally verified. The preliminary results of a measurement survey of airborne pump noise, supported by an extension of the contract, are presented and compared with published sound power levels for pumps. Specific recommendations are made for continuing the effort to understand and control hydraulic noise.

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T b

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FOREWORD

This report was prepared by the Fluid Power Research Center of the School of Mechanical and Aerospace Engineering, Oklahoma State University of Agricultural and Applied Science. The study was initiated by the Mobility Equipment Research and Development Center, Fort Belvoir, Virginia. Authorization for the study reported herein was originally granted by Contract No. DAA02-71-C-0074 and continued under Contract No. DAAK02-72-C-0172. The effective period for the first contract was modified to be October 1, 1970, to September 30, 1972. The effective period for the second contract was November 9, 1971, to November 8, 1972.

The Contracting Officer's Representative was Mr. Hansel Y. Smith, and Mr. John Karhnak served as the Contracting Officer's Technical Representative. Mr. Paul Hopler has effectively represented the Contracting Officer both administratively and technically throughout both phases of this contract. The active participation of Messrs. Smith, Karhnak, and Hopler during critical phases of the work contributed significantly to the overall success of the program.

This report represents only one of four major sections of the annual report on the Hydraulic Specification Program. The titles of the various sections are listed below:

1. Section I. Hydraulic Cylinder and Seals Specification Study.
2. Section II. Hydraulic System Controls Study.
3. Section III. Hydraulic System Noise Study.
4. Section IV. Hydraulic Hose Specification Study.

The study represented by this report was conducted under the general guidance of Dr. E. C. Fitch, Program Director. Mr. G. E. Maroney served as the Project Engineer for the noise study. Dr. Fitch and Mr. Maroney were ably supported by the FPRC Acoustics Laboratory; technically and experimentally by Mr. L. R. Elliott; experimentally by Mr. J. R. Wells; in statistical control by Mr. G. A. Roberts; and in general coordination by Mr. R. K. Tessmann.

This report presents a detailed account of the experimental verification part of the hydraulic noise study. Test procedures for hydraulic component noise, developed under this contract, are presented and experimentally verified. The preliminary results of a measurement survey of

airborne pump noise, supported by an extension of the contract, are presented and compared with published sound power levels for pumps. Specific recommendations are made for continuing the effort to understand and control hydraulic noise.

CHAPTER I

INTRODUCTION

Recent legislation has stimulated industrial interest in the problem of noise [1]. For this report, "noise" is any vibration which is or can cause airborne vibrations between 100 Hz. and 10,000 Hz Now, more than ever before, users of all types of components and systems must consider component sound power output when they write specifications. The primary objective of the project reported in this document is the establishment of noise requirements for fluid power components. A secondary objective, actually supplemental to the primary objective, is the actual measurement of selected fluid power components from a piece of mobile equipment.

Fig. 1-1 illustrates the program objective and some of the preliminary objectives associated with the project. The rational specification of realistic noise requirements for fluid power components must be based on a thorough understanding of several factors which include: 1) basic acoustical theory, 2) practical means for reducing noise, 3) the relationship between component noise and total system noise, 4) the present capability of the industry to produce "quiet" components, and 5) the accuracy and repeatability which can be obtained with test methods for measuring sound power levels.

Basic acoustical theory serves as the basis fc understanding all of the factors associated with fluid power noise. Unfortunately, all of the implications of basic theory have not been applied to fluid power components and systems. But, enough is known about airborne noise measurements and the treatment of airborne noise to serve as a guide for attacking noise problems in fluid systems. Merging the basic characteristics of fluid systems and basic acoustical theory leads to the realization that three types of noise are associated with fluid systems (See Fig. 1-2). The three types of noise are: airborne, structureborne, and fluidborne.

During the past decade, procedures have been written for measuring the airborne noise emitted by fluid power pumps and motors [2, 3]. However, no industrially accepted test procedures exist for the measurement of structureborne or fluidborne noise. In fact, there does not seem to be any published data which establishes the accuracy or repeatability of the industrially accepted test methods for measuring the airborne noise of pumps and motors.

Several manufacturers have published sound power levels or sound pressure levels for components. Since reported sound levels are generally greater than or equal to the actual output level (airborne noise) of the com-

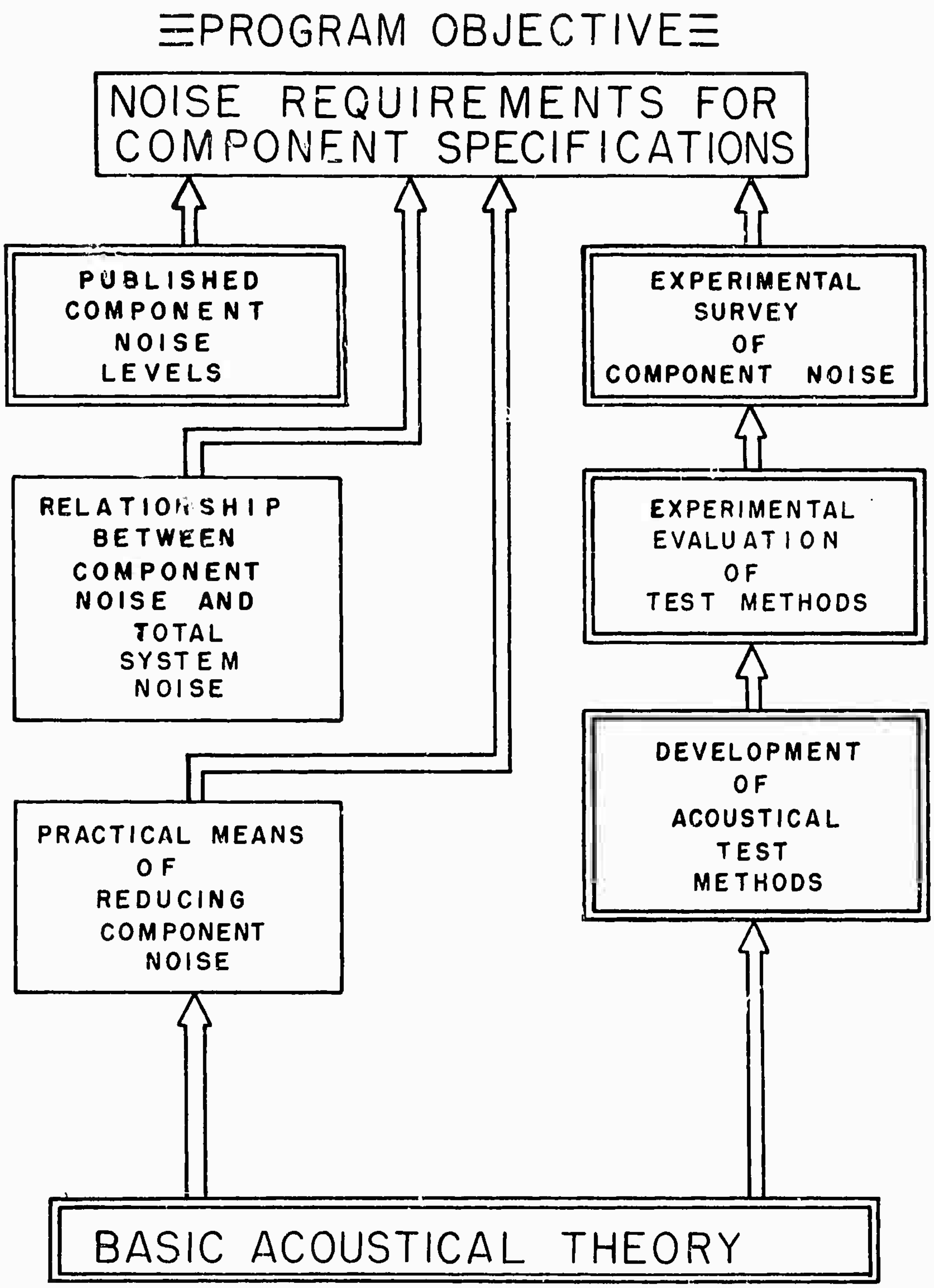


Fig. 1-1. Overall Program Objective Showing Some of the Necessary Supplemental Efforts.

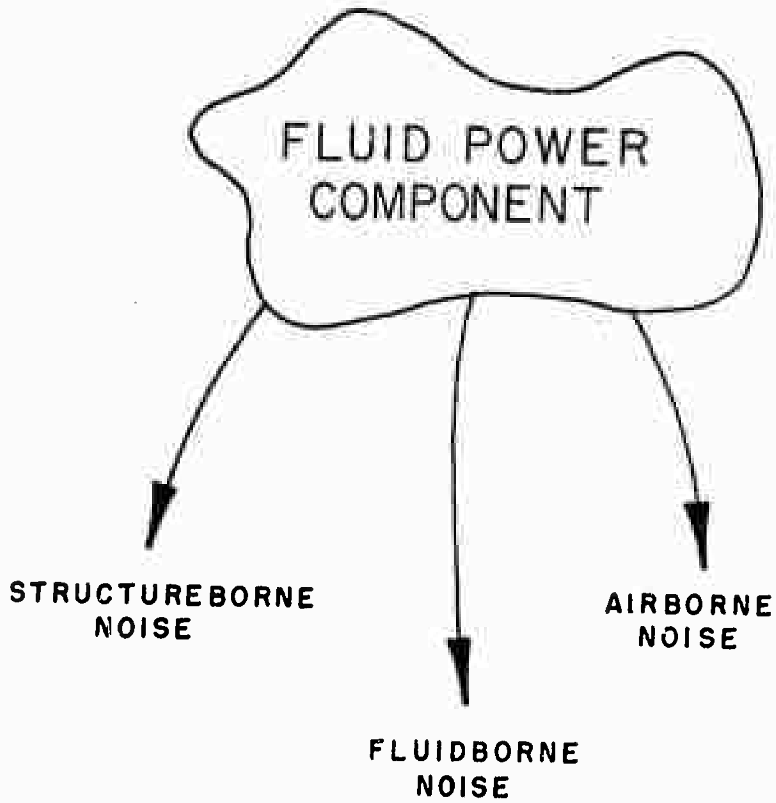


Fig. 1-2. Illustration of the Three Types of Noise Associated With Fluid Power Components.

ponent, these published values might be used for an upper limit. However, since little was published prior to this report regarding the standard deviation of sound level measurements for fluid power components, there has been a great deal of uncertainty associated with making any assumptions about true sound levels of modern fluid components. Many advertisements of fluid power components might lead the reader to believe that fluid pump noise is not a problem. This can occur because the published sound levels, for airborne noise only, are considerably less than the upper noise limits established by legislation.

Recent tests have shown that 100 feet of high-pressure hose can produce over 90dBA sound pressure level at three feet in a hemispherically divergent field. The energy for this noise originates as pressure pulsations in the pump. Thus, even if the equivalent hose length were reduced from that in the test, it is conceivable that a total system noise picture such as that illustrated in Fig. 1-3 might be obtained. It can be seen that, even though none of the individual sources of noise for the total system exceeds 86dB, the total system level is in excess of 90dB. The importance of measuring, reporting, and limiting fluidborne noise has been verified by tests reported in this document.

During this project, several objectives were pursued simultaneously. A major effort was oriented toward developing a reliable test method for the measurement of airborne noise directly emitted from fluid power pumps. Preliminary techniques for measuring fluidborne noise were discussed with members of the industry. The latter discussions led to the development of a fluidborne noise document, which is currently being evaluated. Theoretical evaluation of the measurement of airborne noise yielded equations which will allow accurate measurement in industrial environments previously thought unacceptable.

An experimental evaluation of airborne measurement methods for fluid power pumps has pointed the way to procedure modifications which can yield acceptable repeatability within and between laboratories. A new approach to the measurement of background noise offers the potential for reducing the uncertainty associated with the measurement of the airborne noise of fluid power components.

Both published airborne sound levels for pumps and the results of an experimental survey conducted under controlled test conditions are reported in this document. The results of fluidborne noise measurements are also reported in this document.

The final chapter of this report makes specific recommendations based on the results of actual tests. These recommendations include practical objectives of both a developmental and research nature which would allow attacking the principal causes of noise in fluid power systems as well as establishing realistic limitations for airborne, fluidborne, and structureborne noise in component and system specification.

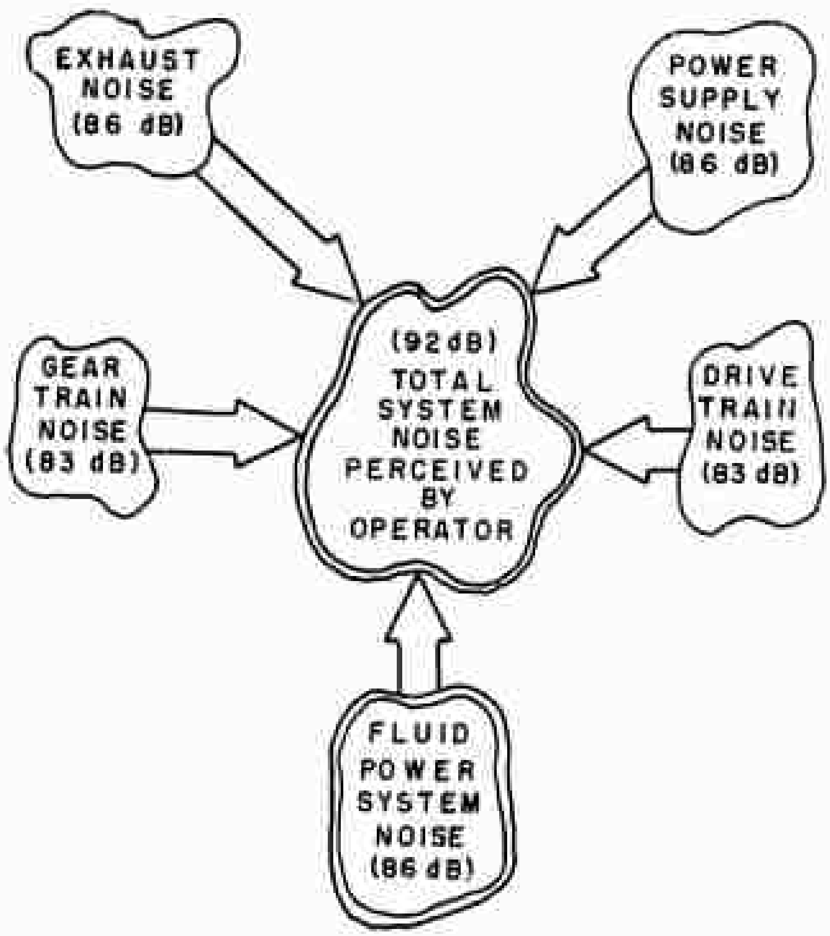


Fig. 1-3. Total System Noise as a Function of Several Sources, Including the Fluid Power System.

CHAPTER II

TEST PROCEDURE DEVELOPMENT

The objective of this phase of the project is the acquisition of acoustical test methods which are acceptable to the fluid power industry. Three test methods are needed, one method for each of the three types of noise found in fluid power systems. During this project period, project members participated in the development of an industrially recognized airborne noise test procedure. With the guidance of the industry, a preliminary test method for measuring and reporting fluidborne noise was developed. Both of the recently developed test methods are discussed in this chapter.

- TEST METHOD -- AIRBORNE NOISE -

The prodigious task of developing an improved test method for the measurement and reporting of airborne noise was facilitated by current events in the fluid power industry. The first airborne test methods proposed to the industry by the FPRC were discussed during meetings at Oklahoma State University. After these meetings, project personnel modified the original proposed test method for airborne noise. While project personnel were evaluating the FPRC proposal, current events in the fluid power industry prompted the formation of a Tri-Level Conference on noise.

The Tri-Level Conference on noise was convened by the American National Standards Institute, the U. S. Technical Advisory Group (USTAG) to the International Standards Organization (ISO), and the National Fluid Power Association (NFPA). FPRC personnel were active in the Conference and worked diligently to insure that the resultant airborne noise document represented the latest accepted thinking in fluid power industry. Members of the Tri-Level Conference who participated in the development of the NFPA test procedures for airborne noise indicated that the new document represented a significant advancement for the industry. The new Test Method for Airborne Noise is presented in Appendix G.

The reader is encouraged to review Appendix G. It should be recognized that the test method in Appendix G relies on accepted ISO acoustical documents for the major acoustical requirements. From a fluid power point of view, the important feature of the document is the recognition of the numerous items which contribute to the overall sound power level in a sound measurement environment.

The document presented in Appendix G can be extended to any type of

fluid power component. As illustrated in Fig. 2-1, airborne noise measurements can be made on fluid power pumps, motors, valves, and conduits. The airborne noise document (AND) was directed toward hydraulic pumps with the understanding that it could be extended to the other fluid power components.

The center portion of Fig. 2-1 directs the reader's attention to the characteristics of the test facility, and instrumentation, and the installation of the component. The AND allows measurements to be taken in any acceptable acoustical environment. The test environment must be certified by the appropriate procedure contained in ISO R-1680 [4]. ISO R-1680 also recommends tolerances for the instrumentation. Those characteristics of the noise source installation that are peculiar to fluid power systems are recognized in the AND.

One of the principle topics of this report is the proper installation of fluid power components in the measurement environments. Although more is presented later about component installation in the sound measurement environment, it is well to recognize at this point that the addition of drive shafts, pump mounts, mount supports, and fluid lines complicates the determination of the actual sound power level of a fluid power pump.

There are several possible ways of presenting the results of a sound level measurement. A few of these methods are presented in Fig. 2-1. The AND requires a presentation of octave sound levels versus frequency and an "A" weighted total sound power level.

- TEST METHOD -- FLUIDBORNE NOISE -

The proposed test method for measuring and reporting fluidborne noise is presented in Appendix H. The intent of the document is to parallel the AND as closely as possible. It is anticipated that both the airborne and fluidborne noise measurements can be obtained using the same test set-up, if it is desired to do so.

It is shown in Chapter IV that fluidborne noise is a significant contributor to the overall sound power level in fluid systems. Although other data exist to verify the importance of fluidborne noise [5], no known standard exists in the fluid power industry for the measurement and reporting of this phenomenon.

The general consensus at the Tri-Level Conference was that fluidborne noise is a significant contributor to system noise There are some members of the industry who contend that pump fluidborne noise is more imported than directly-emitted, airborne pump noise. The limited data that is available supports this contention. It is questionable that the industry has been measuring and reporting the most important fluid power noise.

The fluidborne data presented in this report was obtained in a manner similar to that recommended by the proposed test procedure for measur-

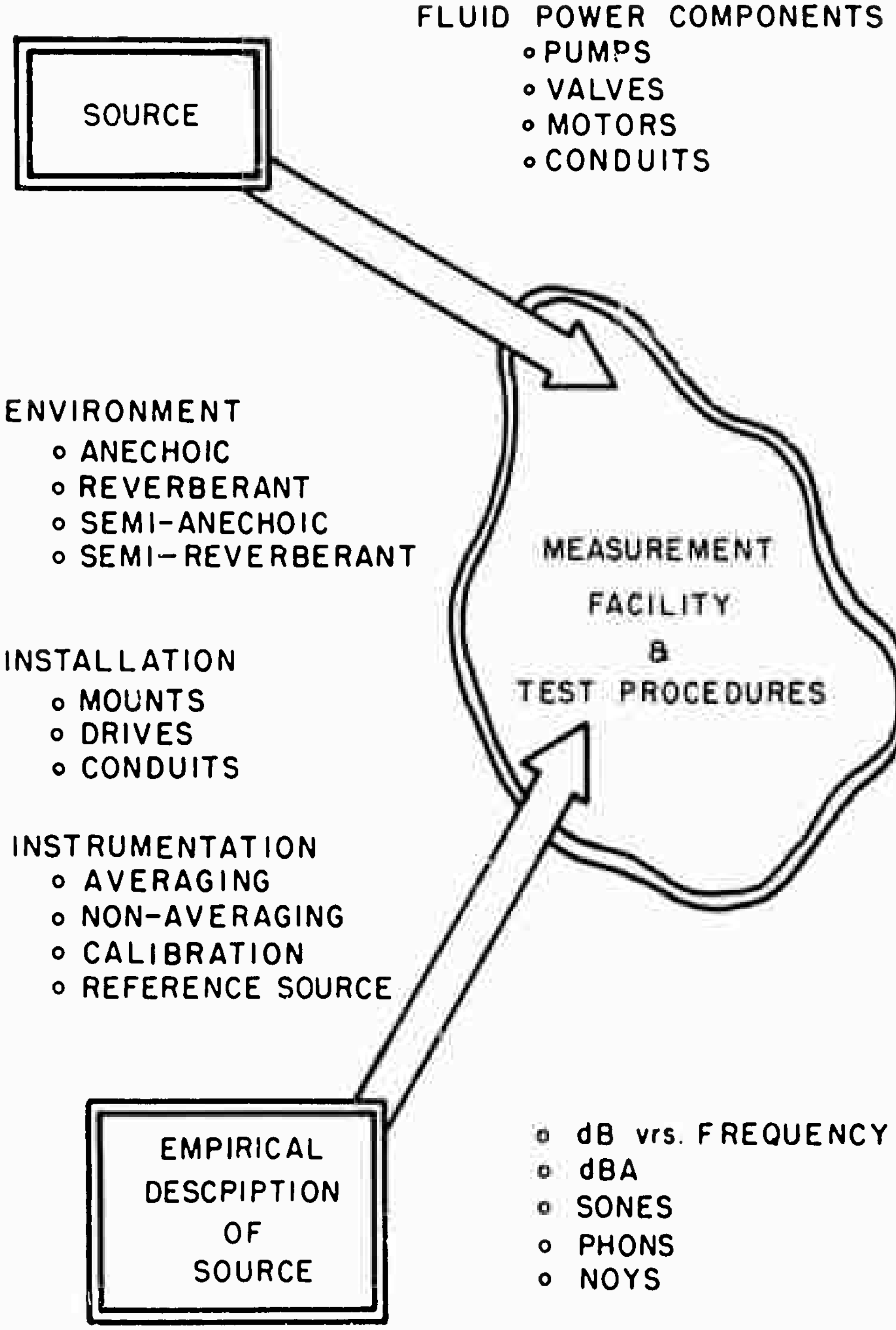


Fig. 2-1. Considerations for Airborne Noise Test Method.

ing fluidborne noise. It is reasonable to expect that a large degree of confidence can be attached to component comparisons based on the data. However, the exact degree of confidence associated with any reported fluidborne measurements will not be known until adequate controlled testing is accomplished.

The document in Appendix H is a reasonable starting point for the development of a fluidborne measurement procedure. Numerous members in the industry have suggested proceeding with investigations based on the proposed method.

CHAPTER III

THEORETICAL EVALUATION OF AIRBORNE NOISE MEASUREMENT PROCEDURE

Test method evaluation has been a continuous project objective. The true merit of any test method becomes apparent once the procedures are implemented in the laboratory. The airborne test method proposed by the Tri-Level Conference was examined both theoretically and experimentally. This chapter discusses the theoretical evaluation of the procedure. Chapter IV presents the results of the experimental evaluation of the recommended procedure. The results of the theoretical evaluation were used throughout the experimental evaluation. The data reduction techniques developed in this chapter extend the capabilities of practical measurement environments and allow accurate and repeatable measurements.

Fig. 3-1 diagrammatically illustrates a reverberant measurement facility. A reverberant facility is used for an example, but the resultant techniques can be applied to any measurement facility. For the purposes of using a realistic example, assume that a fluid power pump is the test unit, or unknown source, whose sound power level is desired.

As shown in Fig. 3-1, the test environment contains: a diffuser, a reference source, a pressure transducer (microphone), a drive and support system, and the test unit. The outside environment includes instrumentation, controls, and a drive system, or power supply, for the pump to be tested.

If the test environment were ideal and the drive and support system for the pump made no noise, then the diffuser and reference source could be removed from the test environment and measurements could be made which would accurately reflect the characteristics of the pump. Unfortunately, the real world precludes that luxury.

The first step toward dealing with the real world might be to recognize that the drive and support will make some noise. If it does, and they do, then it is a relatively simple matter to measure the background noise from the drive and support and subtract it from the measurements made while the pump is operating under test conditions. Thus, it is obvious that any practical environment will have some background noise level which will affect sound measurements. The more ideal the test system and environment, the more negligible the background effects.

Extending the idea of background noise a little further allows an accounting to be made for noise from diffusers and the outside environment. If the diffuser does not make any noise and no noise enters the measurement environment from the outside, then the data reduction process

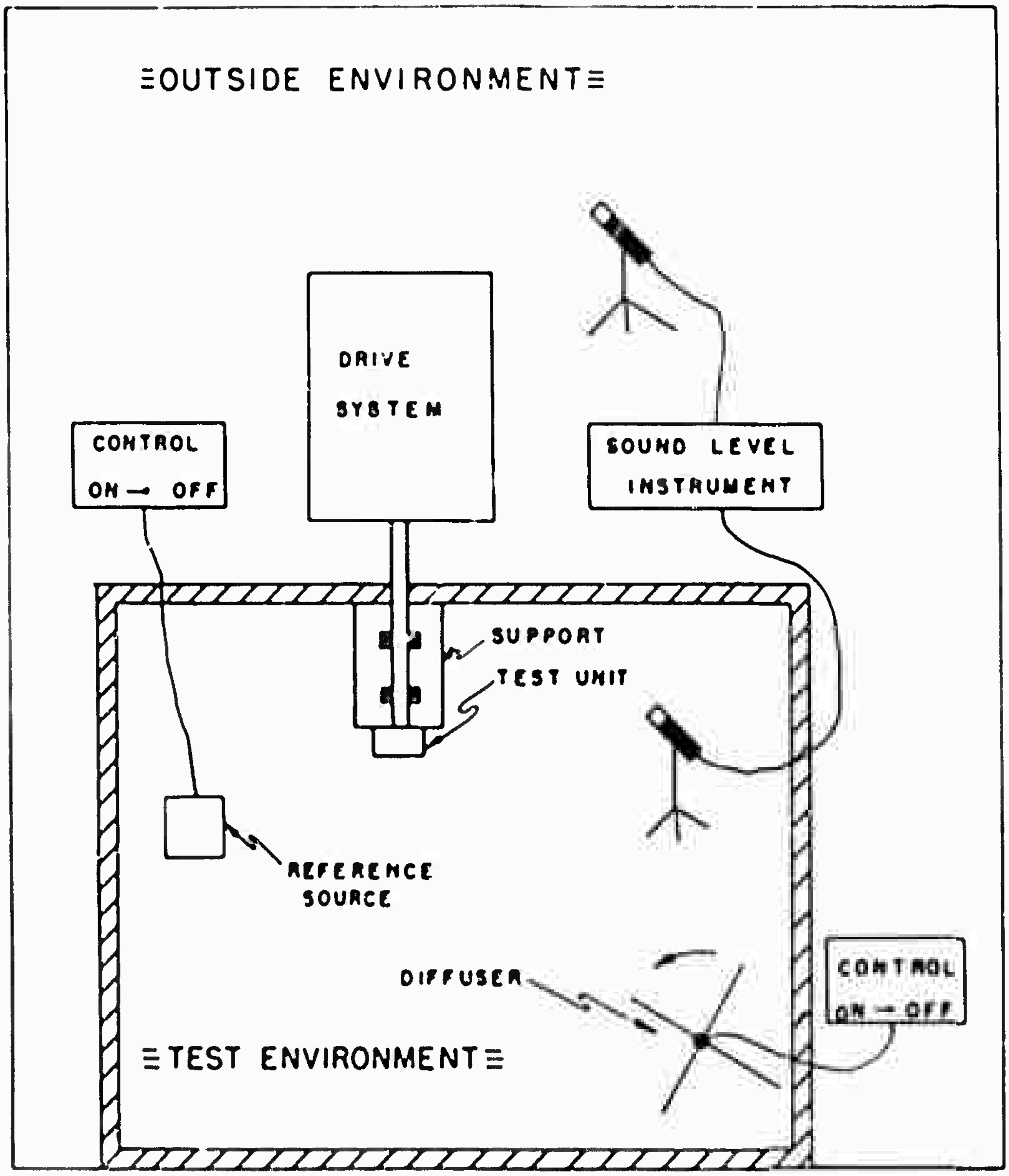


Fig. 3-1. Noise Measurement Facility

is simplified. But, in general, background noise from the diffuser and the outside environment must be considered in the data reduction procedure

The apparent background (B_a) that exists during a test is a function of several noise sources. The background sources for the example include: the building background (B), the sound output of the diffusers or vanes (V), the output of drive and support system (D_s), and the noise that is transmitted through the walls from the outside environment.

Prior to defining data reduction expressions, it is necessary to consider the purpose of the reference source. A calibrated sound reference source allows noise data to be corrected for the imperfections of the test facility. A correction for measured data is determined by comparing the certified levels (R_c) for the reference source to measured sound levels for the reference source. Each time a data run is made on an unknown source, a run is made on the reference source.

For example, if it is desired to determine the background in the test environment due to the surroundings, then a measurement would be made in the test room (B_2); and subsequently, the reference source would be measured (R_{2b}) in the test room. An ILC Reference Source has an output above 70dB at most 1/3 octave center frequencies between 100 Hz and 10,000 Hz. If the measured level in the room (B) is 55dB or less, then it is reasonable to assume that B did not affect the measurements R_{2b}. This reasoning allows the definition of the background B as:

$$B = \left\{ B_2 + R_c - \left[R_{2b} - \cancel{B} \right] \right\} \tag{3-1}$$

The brackets [ ] in Eq (3-1) indicate that an operation on powers is required; the braces { } indicate that an operation in decibels is required. In the case of Eq. (3-1), if B were significant relative to R_{2b}, than a power correction of the measurement R_{2b} would be necessary. The difference between the certified reference level, R_c, and the measurement R_{2b} is a correction for the facility in dB and can be added directly to a dB reading for B_2.

Given the background sound power (B) in the room, a measurement of the vane noise (V_2), and an associated reference measurement (R_{2v}), it is possible to determine the sound power of the vane, V. Eq. (3-2) shows the relationship between V, the measurements, and the background.

$$V = \left[\left\{ V_2 + R_c - \left[R_{2v} - B \right] \right\} - B \right] \tag{3-2}$$

Since the sound level in an industrial type sound measurement environment can be influenced by the outside sound level, it is important to examine the attenuation of the walls of the test environment. One measurement which is needed for this examination of the wall attenuation or transmis-

sion loss (T_L), is the background outside (B_1) of the test environment. Data needed to complete the evaluation of T_L include a measurement outside during the test (T_{1L}), a measurement inside the environment during the test (T_{2L}), and an associated measurement of the reference source (R_{2L}). This data can be combined according to Eq. (3-3) to yield T_L.

$$T_L = \left[T_{1L} - B_1 - \left[\left\{T_{2L} + R_c - \left[R_{2L} - V - B\right]\right\} - V - B\right]\right] \qquad (3\text{-}3)$$

Once V, B, and T_L are available, tests can be conducted to determine the sound power output of the drive and support system. One recommended approach for obtaining background measurements involves disconnecting the drive coupling at the test pump and then measuring the noise output when the drive is operating at test speed. For this test condition, three measurements are needed: the level outside the environment, D_1; the level in the test environment, D_2; and a reference measurement, R_{2d}. The sound power output of the drive and support system, D_s, can be determined from the following expression:

$$D_s = \left[\left\{D_2 + R_c - \left[R_{2d} - V - B\right]\right\} - V - B - \left\{\left[D_1 - B\right] - T_L\right\}\right] \qquad (3\text{-}4)$$

The apparent background, B_a, that exists during a test can be calculated using Eq. (3-5)

$$B_a = \left[\left\{\left[T_1 - B_1\right] - T_L\right\} + D + V + B\right] \qquad (3\text{-}5)$$

The measurement T_1 is the level outside the test room during the test of the pump.

The measurement of the pump operating at test conditions is S_2. The reference measurement associated with S_2 is R_{2s}. With these measurements, T_1, and Eq. (3-5) for B_a, it is possible to express the sound level of the source as:

$$S \doteq \left[\left\{S_2 + R_c - \left[R_{2s} - V - B\right]\right\} - B_a\right] \qquad (3\text{-}6)$$

It is important to point out that Eqs. (3-1) through (3-6) represent manipulations of the measurements at a single center frequency. These equations apply to linear combinations of individual levels, but they do not apply in general to the combination of weighted levels. For example, these equations cannot be used to directly correct dBA measurements. The important point is that the equations do apply prior to weighting levels. Afterwards, they can be combined for "A" weighted total levels.

In an ideal facility, neglecting the fluid lines and pump mount, it would be possible to make one measurement and have the sound level for a

pump. In an industrial measurement facility, it would be best to use the complete set of Eqs. (3-1) through (3-6). The use of equations such as those presented will reduce the measurement variation between laboratories.

Table 3-1 is a complete worksheet for computing the sound level of a component. Once initial values are established for the background measurements, the worksheet can be reduced. Table 3-2 shows a reduced worksheet for calculating the sound power level of a component. For a given test, a maximum of three measurements would have to be made and recorded in the latter table. The remaining five rows of the first eight rows would already be completed based on previous tests. The table could be readily completed using a hand calculator or a set of tables. Of course, the data could be entered directly into a digital computer, which would do the computations and present the results of the data reduction.

The remaining section of this chapter discusses a computer program for implementing the data reduction technique presented in Eqs. (3-1) through (3-6).

- AIRBORNE NOISE-COMPUTER PROGRAM -

The airborne noise-computer program presented in Appendix B is written in the Fortran IV language. The data reduction procedure is outlined in the first section of this chapter. The program inputs are the measured sound levels in dB of the backgrounds, reference source, and component being measured. The values for the transmission loss of the reverberant room wall are not calculated by the computer. The same transmission loss applies to all tests in a given room. The transmission loss results obtained from Eq. (3-3) are used as inputs to the computer. The program corrects the measured levels for a component using the background data. The correction procedure requires the proper addition and subtraction of the measured levels.

The linear addition and subtraction of sound levels is not accurate for levels measured in decibels. A simple transformation to power makes it possible to perform these calculations. For example, if the measurement level in a given 1/3 octave band is 76dB and the background level is 72dB, how is the actual level of the source corrected to account for the background? First, the dB levels must be converted to power. This may be accomplished with the expression [7]:

$$\text{POWER} = 10^{(\text{dB}-74)/10} \tag{3-7}$$

The power associated with 76dB is 1.58, and the power associated with 72dB is 0.63. The background-corrected power for the source is:

$$\begin{aligned} \text{PWR(B)} &= \text{PWR(76)} - \text{PWR(72)} \\ \text{PWR(B)} &= 0.95 \end{aligned} \tag{3-8}$$

TABLE 3-1

COMPLETE WORKSHEET FOR SOUND POWER LEVEL (dBA)

[ ] ≡ ADD AS POWERS {} ≡ ADD AS dB

	LINE NO.	CENTER FREQUENCY, (HZ) / VARIABLE	125 (HZ)	250 (HZ)	500 (HZ)	1,000 (HZ)	2,000 (HZ)	4,000 (HZ)	8,000 (HZ)
	1	B_1							
	2	B_2							
	3	D_1							
	4	D_2							
	5	R_C							
	6	R_{2B}							
	7	R_{2D}							
	8	R_{2S}							
	9	R_{2L}							
	10	R_{2V}							
	11	S_2							
	12	T_1							
	13	T_{1L}							
	14	T_{2L}							
	15	V_2							
	16								
	17	[5-6]							
B	18	{2+17}							
	19	[10-18]							
	20	{5+15-19}							
V	21	[-18+20]							
	22	[-1+13]							
V+B	23	[18+21]							
	24	[9-23]							
	25	{5+14-24}							
	26	[-23+25]							
T_L	27	[22-26]							
	28	T_L(G)							
	29	[7-23]							
	30	{4+5-29}							
	31	[-1+3]							
	32	{31-28}							
D_S	33	[-23+30-32]							
	34	[-1+12]							
	35	{34-28}							
B_A	36	[23+33+35]							
	37	[8-23]							
	38	{5+11-37}							
S	39	[-36+38]							
	40	dBA CORR.							
L_U	41	{39+40}							

TABLE 3-2

REDUCED WORKSHEET FOR
SOUND POWER LEVEL (dBA)

[ ] ≡ PWR   DRIVE SPEED ________ RPM   { } ≡ dB

LINE NO.	CENTER FREQUENCY HZ / VARIABLE	125 (HZ)	250 (HZ)	500 (HZ)	1,000 (HZ)	2,000 (HZ)	4,000 (HZ)	8,000 (HZ)
1	B_1							
2	D_S							
3	R_C							
4	R_{2S}							
5	S_2							
6	T_1							
7	T_L							
8	V + B							
9	[−1+6]							
10	{−7+9}							
11	[2+8+10]	B_A, APPARENT BACKGROUND						
12	[4−8]							
13	{3+5−12}							
14	[−11+13]	S, SOURCE LEVEL						
15	dBA CORR.							
16	{14+15}	L_U, CORRECTED LEVEL						

$$\sum_{i=1}^{7} [16_i] = \_\_\_\_\_\_\_\_ \text{ dBA TOTAL POWER}$$

The background corrected source level in dB may then be computed using the expression:

$$dB = 10\left[\log_{10}(PWR)\right] + 74 \qquad (3\text{-}9)$$

For the example, the corrected sound level is 73.8dB for the source.

This method of adding and subtracting sound levels is used extensively in the computer program and provides significantly more accurate results than other techniques.

The program output is shown in Table 3-3. Columns 1 and 10 are the 1/3 octave band center frequencies used by the program. The other output columns are described below.

TABLE 3-4

DESCRIPTION OF AIRBORNE NOISE PROGRAM OUTPUT PARAMETERS

LUB	Measured Level of the Unknown Source
LRB	Measured Level of the Reference Source
LR	Calibrated Level for the Reference Source
CORR	Correction of LUB Dur to Inconsistencies in Temperature, Humidity, and Room Design
LU	Corrected Sound Level of the Unknown Source (component)
BA	Background Level in the Measurement Environment
VA	Background Level Dur to the Acoustic Diffusers
PWR	dBA Weighted Power
DBA	DBA Levels for the Unknown Source (Component)

The program also prints total unweighted sound power, "A" weighted power, dBA weighted sound power, and dBA weighted sound power three feet from the source in a hemispherically divergent field. The system parameters are self-explanatory. The values for the system parameters are read into the computer at the beginning of the program.

TABLE 3-3. AIRBORNE NOISE COMPUTER PROGRAM OUTPUT

OSU-FPRC
ACOUSTICS LABORATORY DATA LOG

FREQ	LUB	LRB	LR	CORR	LU	BA	VA	PWR	DBA	FREQ
100.	57.3	68.7	72.0	3.4	39.0	61.9	52.2	0.0000	19.9	100.
125.	62.7	71.7	75.5	4.1	39.0	73.4	59.7	0.0000	22.9	125.
160.	56.8	72.8	75.5	2.8	39.0	63.1	53.5	0.0000	25.8	160.
200.	59.9	75.9	75.5	-0.4	56.4	56.6	48.2	0.0015	45.6	200.
250.	74.2	75.7	75.5	-0.2	73.7	62.5	48.5	0.1286	65.1	250.
315.	66.8	75.7	76.0	0.3	66.1	60.5	52.6	0.0359	59.6	315.
400.	61.3	74.7	75.0	0.4	59.2	58.1	57.6	0.0110	54.4	400.
500.	63.9	73.3	76.0	2.9	63.7	63.9	59.6	0.0432	60.4	500.
630.	71.1	73.7	75.5	1.9	72.7	60.3	56.0	0.4824	70.8	630.
800.	71.4	74.2	76.0	1.9	72.5	65.2	55.8	0.5913	71.7	800.
1000.	64.8	74.2	75.5	1.3	64.9	60.0	52.4	0.1239	64.9	1000.
1250.	59.0	74.7	75.5	0.8	55.2	58.0	50.8	0.0147	55.7	1250.
1600.	58.2	75.1	76.0	0.9	39.0	64.5	52.0	0.0004	40.0	1600.
2000.	56.7	74.9	75.5	0.6	53.1	55.2	48.8	0.0107	54.3	2000.
2500.	58.6	75.2	76.0	0.8	57.2	55.5	52.8	0.0275	58.4	2500.
3150.	57.0	74.9	75.5	0.6	54.3	54.9	50.0	0.0141	55.5	3150.
4000.	56.9	73.6	75.0	1.4	57.7	49.8	48.5	0.0292	58.7	4000.
5000.	57.3	73.1	75.0	1.9	58.4	51.3	47.4	0.0312	58.9	5000.
6300.	58.3	73.3	74.5	1.2	59.2	48.4	46.9	0.0313	59.0	6300.
8000.	59.0	72.9	75.0	2.1	60.8	48.9	48.4	0.0376	59.7	8000.
10000.	56.3	67.3	71.5	4.2	60.4	46.7	46.5	0.0248	58.0	10000.

UNWEIGHTED SOUND POWER ------------- 78.84 DB
TOTAL "A" WEIGHTED POWER ------------------------------ 1.6394
"A" WEIGHTED SOUND POWER --- 76.15 DBA
THREE FEET FROM THE SOURCE IN A HEMISPHERICALLY DIVERGENT FIELD*** 69.15 DBA ***

SYSTEM PARAMETERS FOR OSU-MP-10
PRESSURE= 200PSI SPEED=2[illegible]0RPM TEMPERATURE=38.0C FLOW RATE=26.8G INLET= 0PSI

CHAPTER IV

EXPERIMENTAL EVALUATION OF AIRBORNE NOISE MEASUREMENT PROCEDURE FOR FLUID POWER PUMPS

The primary objective of experimentally evaluating the airborne noise test method is to determine the degree of confidence which can be associated with the reported measurements. The degree of confidence associated with a set of data can be established statistically. Statistically, the degree of confidence is related to the standard deviation. Small standard deviations, or variations between measurements, allow a high degree of confidence. Large variations between measurements reduce the degree of confidence in those measurements. There are five major areas for variation in the airborne noise test: 1) variations in installation of the component and its support equipment, 2) variations in measurements due to the test facility, 3) variations in the measurement procedure, 4) variations in the procedure for reducing the test data, and 5) variations to the actual output of the device under test.

The importance of minimizing each possible variation can be emphasized by reviewing a method for predicting the total error caused by a group of errors. Total tolerances or errors are often predicted by taking the square root of the sum of the squares of the individual errors. If each of the five possible variations is 1dB, then the total predicted variation is 2.24dB. However, if each variation is controlled to 0.5dB, then the predicted total variation is 1.12dB.[1] If a component manufacturer or user is looking for differences in the sound power levels of components, then the test errors must be minimal in order for the differences to be apparent.

Variations in the sound output of the unit to be tested should be averaged during the test. It was impractical to control these variations which are due to normal component characteristics.

No formal attempt has been made to evaluate the insignificant variations which can occur due to the techniques used for data reduction.

The three principal sources of variation between measurements examined are: 1) varations due to the test facility, 2) variations due to

[1]For the purposes of the example, arithmetic operations on dB are acceptable. In general, arithmetic operations should not be performed on dB. Consider the case of averaging. If two levels that differ by 6dB are averaged arithmetically, the resultant average is 1dB in error.

the installation of the component, and 3) variations due to measurement procedure. Each of these variables is discussed in the following paragraphs.

- FACILITY VERIFICATION -

Introduction

One primary concern of this developmental investigation is the acquisition of test results which allow confident differentiation between measured sound power levels. The immediate goal is to provide measurement techniques that allow accurate distinction between fluid power components for specification purposes. Considering the vast number of environments, types of instrumentation, and fluid power component support systems that can be grouped to provide a measurement facility, the task of accurately and repeatably measuring a given source is formidable. Even the proper combination of environment, instrumentation, and support system will not supply meaningful information without proper verification of the facility's capabilities. This section is concerned with methods of facility verification and means through which the accuracy and repeatability of sound measurements can be improved.

Environment

The test environment plays a dominant role in the overall credibility of measurements obtained in a given facility. Although there are many suitable types of measurement environments, the measurement characteristics of a reverberant environment will be considered in detail for two reasons -- 1) its ease of implementation with respect to fluid power component measurement and 2) the availability of this type of environment for testing by the Fluid Power Research Center.

The ultimate reverberant environment is capable of producing a totally diffuse field. A diffuse sound field is defined as a sound field where a great number of reflected waves from all directions combine in such a way that the average sound energy density is uniform everywhere in the field [5]. A perfectly diffuse sound field is an idealization and unattainable for all practical purposes. Thus, discussions of reverberant environments are constrained to defining how closely a given room approaches diffusivity.

It is well known that the inherent lack of diffusivity within a reverberant environment results from the combination of many reflected sound waves into distinct patterns known as standing waves. The standing wave phenomenon causes areas of varying sound intensity within the measurement field, which renders the field non-diffuse. Without proper modification of the measurement field, errors of five decibels or more can occur for a pure tone source. A pure-tone source radiates sound waves of only one frequency. Fluid power component frequency spectrums often contain dominant pure tones.

Proper verification using a pure-tone test insures repeatability. It is well known that the repeatability of any measurement obtained in a reverberant environment is equal to or better than the repeatability for the measurement of a pure tone. Therefore, modification of a reverberant room to produce the best possible measurement of a pure-tone signal insures the best possible measurement of any source. Acoustical diffusers are one type of modification which evenly distributes the sound energy within the measurement field.

There are two general types of diffusers used to modify the measurement characteristics of reverberant environments -- the moving or rotating plane (vane) and rotating cone or cylinder. Both types are shown in Fig. 4-1. The rotating vane has been installed and tested in the Fluid Power Research Center's reverberant room.

The improvement of measurement repeatability by rotating vanes is demonstrated in Tables 4-1 and 4-2. Table 4-1 shows the improvement with respect to vane speed (RPM) for one vane. Table 4-2 demonstrates the repeatability improvement realized by using more than one vane. These two tables are shown graphically in Figs. 4-2 and 4-3 respectively. Fig. 4-3 shows that, as the rotational speed increases, the sample deviation decreases drastically. The addition of a second vane further decreases the sample deviation of the measurements.

The result of using vanes in the measurement environment is the reduction of the sample deviation by an order of magnitude. The design of vanes and the determination of the proper rotational speed will not be discussed in this report. Full consideration of these topics is presented in the BFPR Annual Report 72 AV-2B [5]. The significance of the reported sample deviations can be understood by considering recommended sample deviations. The Acoustical Society of America (ASA) has published values for the maximum allowable standard deviations. Maximum values are published [6] for both broad-band and pure-tone sources. Fig. 4-4 contains a plot of the maximum allowable standard deviation versus frequency for a broad-band source. A broad-band source emits equal power in all frequency bands. Fig. 4-4 indicates that the Fluid Power Research Center's reverberant room has excellent diffusivity.

According to the ASA, the measured standard deviation of a 315 Hz. pure tone can be as large as 2.0dB. The standard deviation of a 315 Hz. signal in OSU's reverberant facility is .95dB. The recommendations of the ASA do not appear stringent enough to produce repeatable results. The last statement may require clarification. A short example will be presented.

ASSUME: Broad-band noise is being measured in a reverberant room.

GIVEN: For the 315 Hz. 1/3 octave band, the ASA allowable standard deviation for measurements is 1.0dB (See Fig. 4-4).

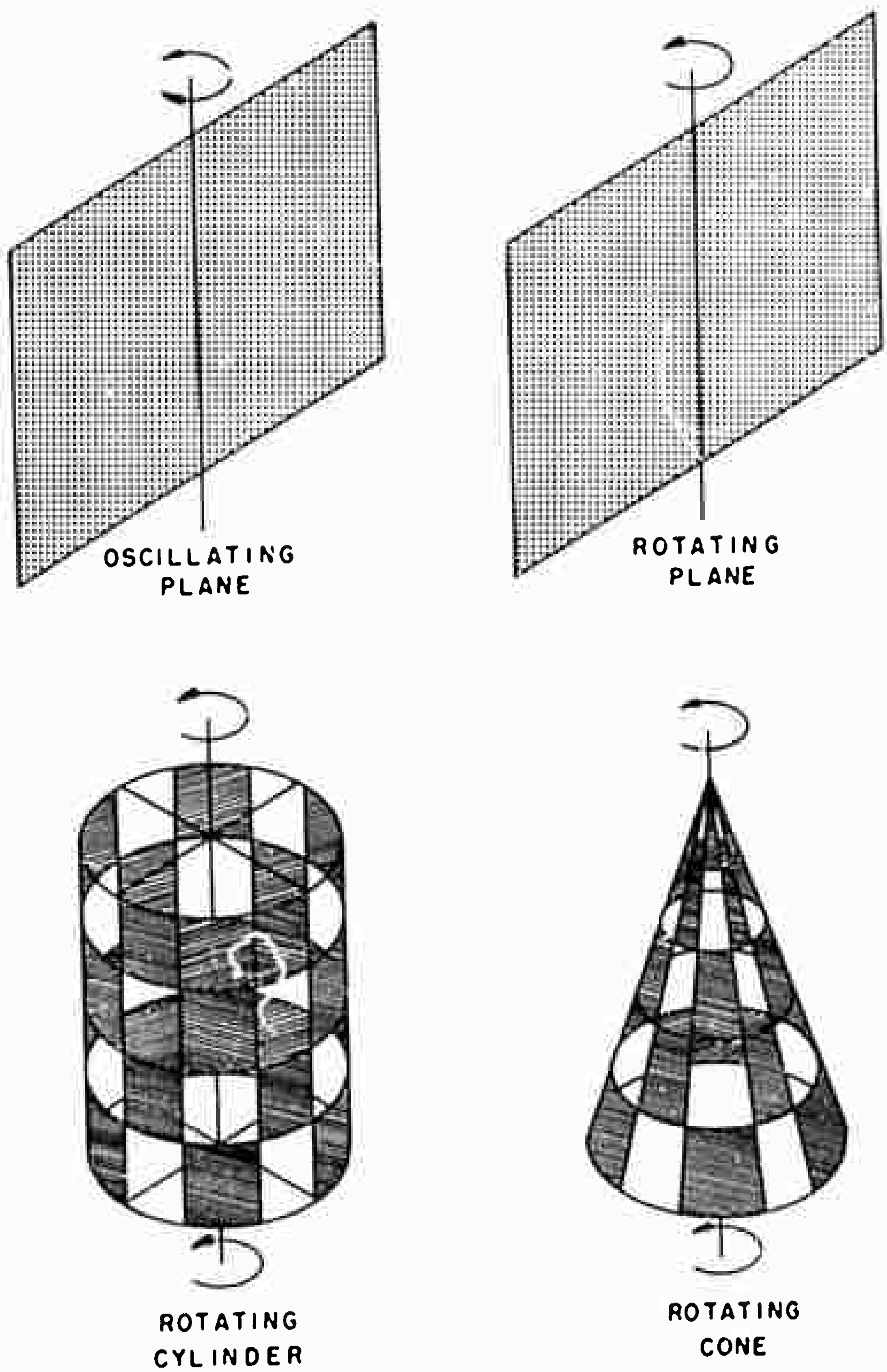


Fig. 4-1. Various Types of Acoustical Diffusers.

TABLE 4-1

SAMPLE DEVIATION(S) IMPROVEMENT

DUE TO INCREASING VANE SPEED

FOR PURE TONE MEASUREMENTS

Microphone Position	Vane Speed (RPM)			
	0	4.3	9.1	16.1
1	97.80	93.10	92.90	91.40
2	84.10	96.25	93.20	89.55
3	87.50	96.75	96.25	93.00
Mean	89.82	94.70	94.11	91.31
S	8.07	2.16	1.98	2.04

TABLE 4-2

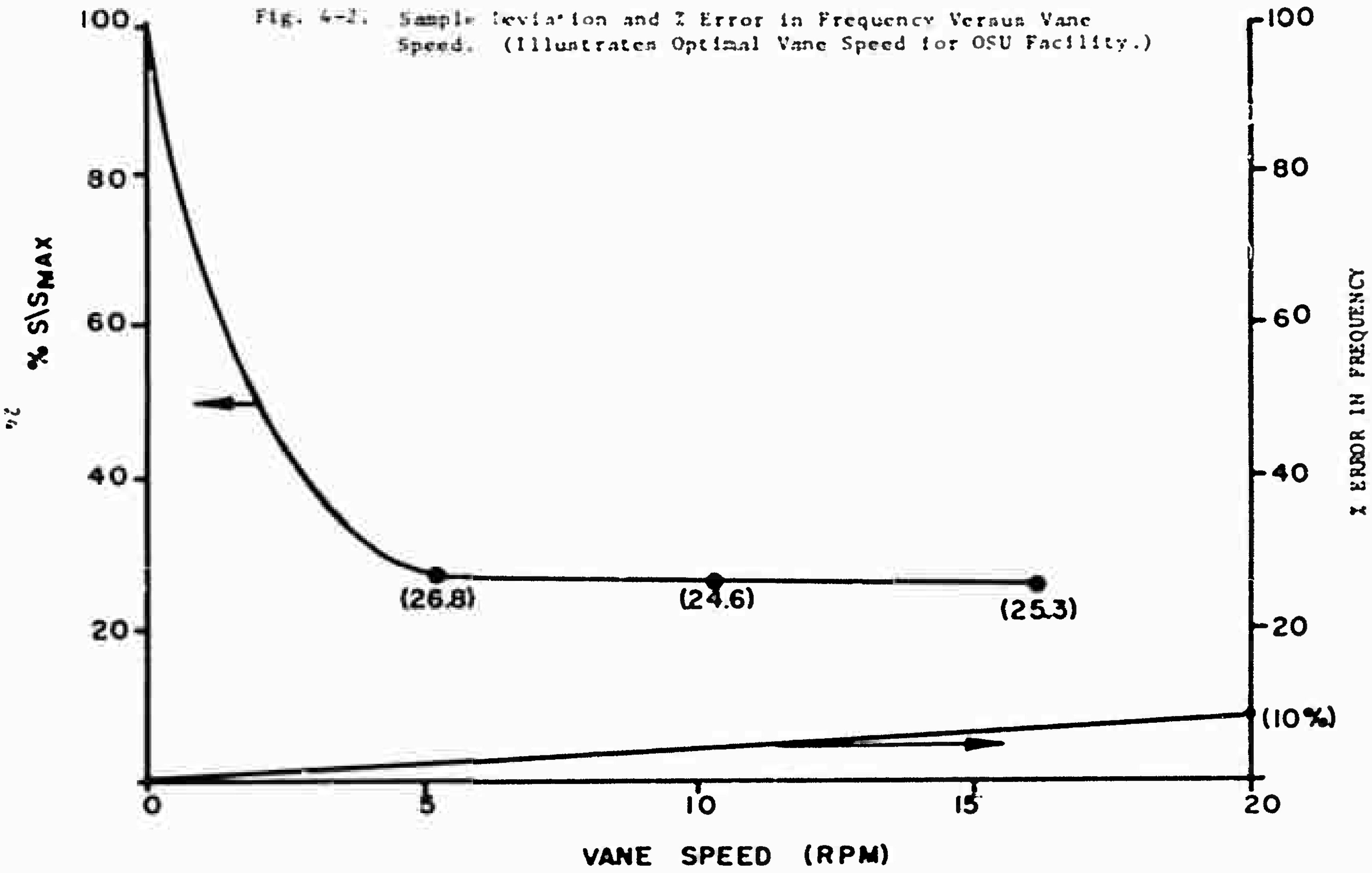
SAMPLE DEVIATION(S) IMPROVEMENT

DUE TO INCREASING THE NUMBER OF VANES

FOR PURE TONE MEASUREMENTS

Microphone Position	No Vane	Vane #1 16.1 RPM	Vane 1 & Vane 2 6.5 RPM & 4 RPM
1	97.80	91.40	93.56
2	84.15	89.55	94.10
3	87.52	93.00	92.50
Mean	89.82	91.31	93.35
S	8.07	2.04	0.95

Fig. 4-2. Sample Deviation and % Error in Frequency Versus Vane Speed. (Illustrates Optimal Vane Speed for OSU Facility.)



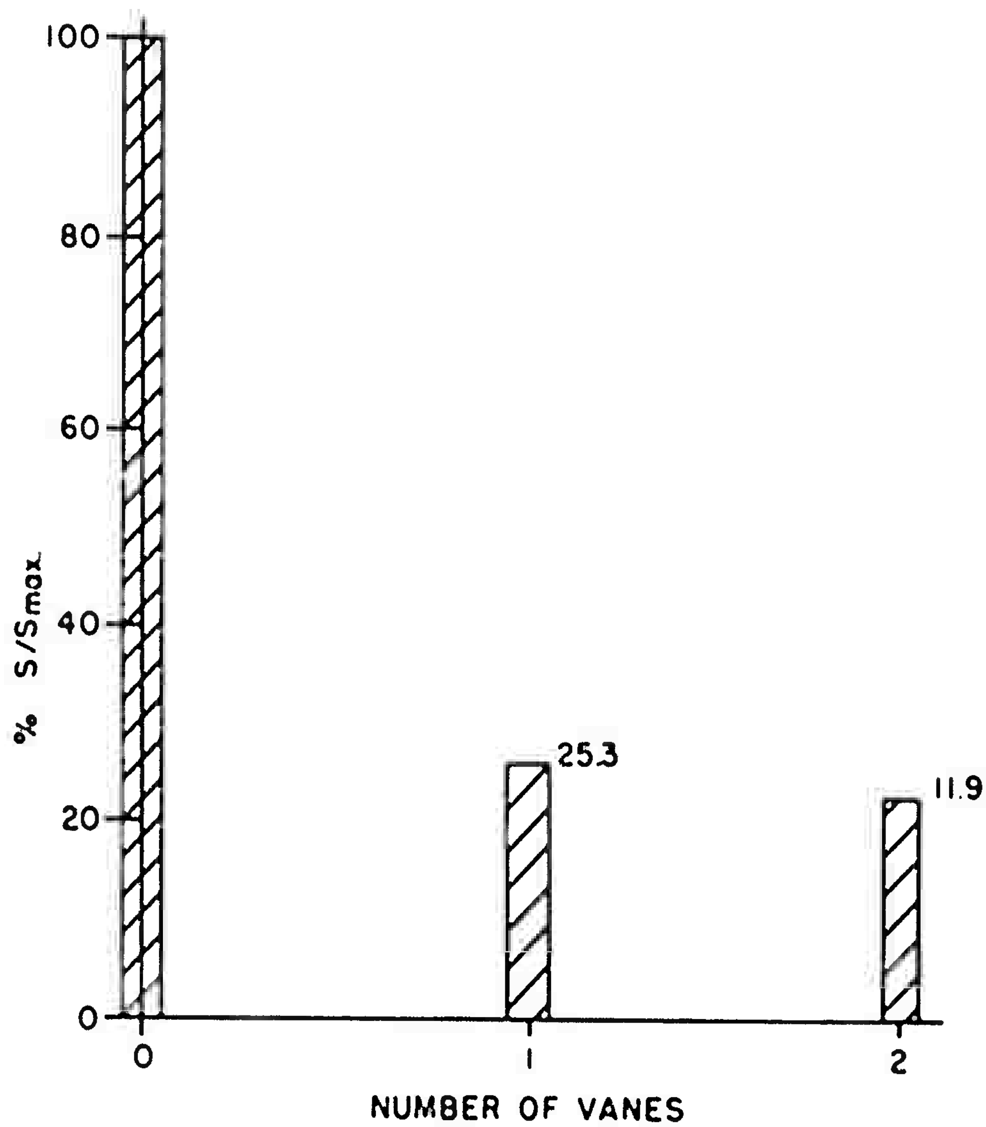


Fig. 4-3. Sample Deviation Versus Number of Vanes for OSU Facility.

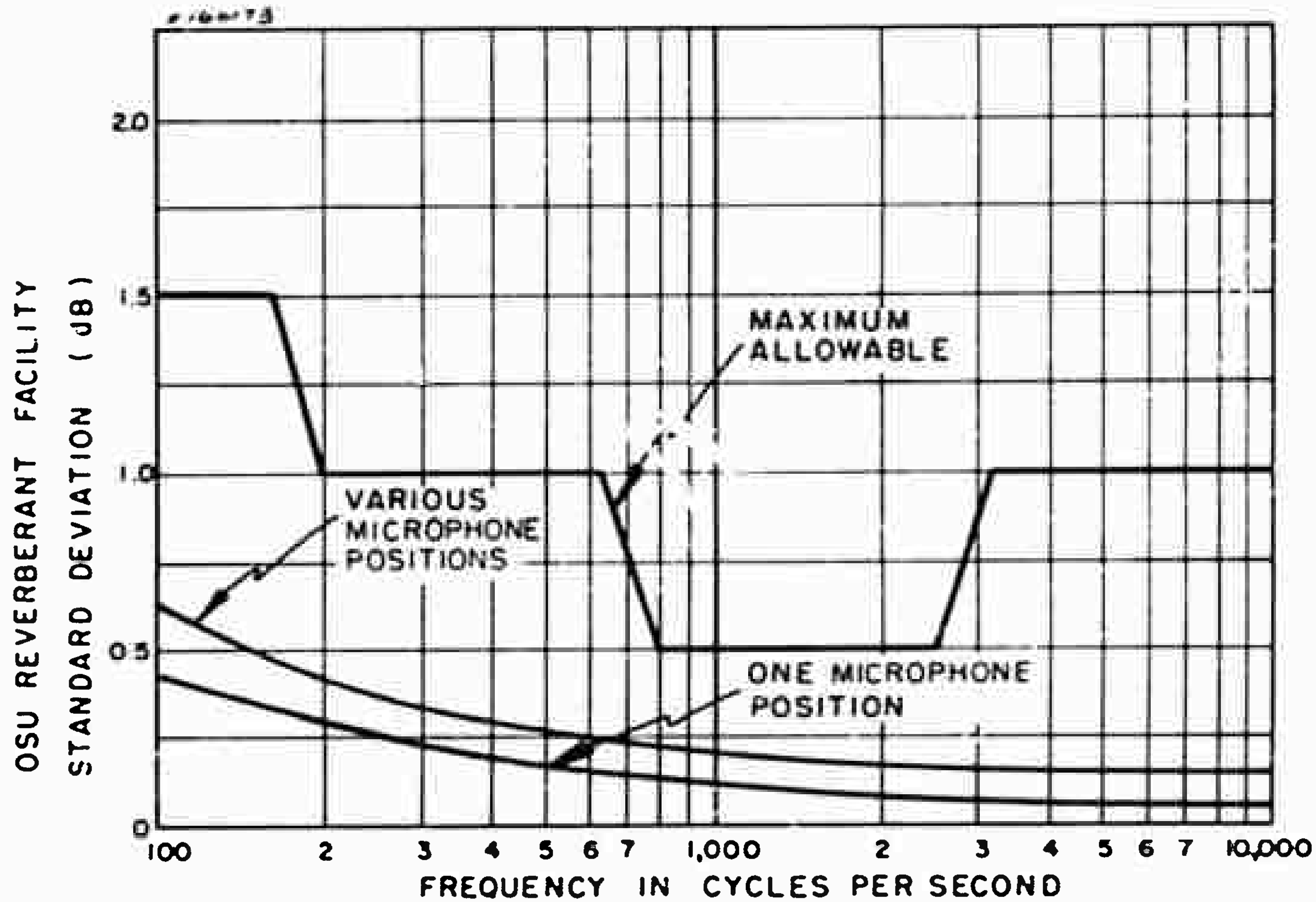


Fig. 4-4. Sample Standard Deviation for a Broadband Source Measured in the OSU Reverberant Room.

The above information yields a 99% confidence that the actual level is within ± 3.0dB of the measured level. For the Fluid Power Research Center's reverberant facility, the standard deviation at 315 Hz. is 0.2dB. This means that in the latter case the 99% confidence level is ± 0.6dB.

This example has been simplified to one 1/3 octave band, but, the same analysis holds true for the total spectrum of fluid power components. The sample deviation of an individual measurement must be significantly less than the sound power deviation associated with all components.

Example: If the sample deviation of an individual measurement is not significantly less than the deviation associated with all components, distinction between components is not possible. This fact is shown graphically in Fig. 4-5. The deviation of the measurements for components A and B is too large to say with any degree of confidence that the actual sound levels of A and B are not the same.

If the sample deviation of an individual measurement is significantly less than the deviation associated with all components, distinction between components is possible with a great deal of confidence. This is shown in Fig. 4-6.

There are various methods of verifying the presence of a diffuse field. One generally accepted method of facility certification is presented in ISO Recommendation R1680 and summarized as follows: Using a broad-band source, take measurements at not less than 10 points on a radius $1/3(V)^{1/3}$ from the source, where V is the volume of the room. Take an equal number of measurements on a radius $2/3(V)^{1/3}$ from the source. Average the measurements taken on each radius for each frequency band of interest. If in any band the difference of the averaged values is greater than 1dB, the measurement field is non-diffuse [4].

This method of facility certification provides a confidence of 95% that the actual level in every band is within ± 1.7dB. More accurate measurement can be insured by requiring that the difference in the averaged levels be less than 1dB.

Instrumentation

Instrumentation must be considered an integral part of the measurement facility. Instrumentation averages the input signal to produce an output. The length of time the instrumentation averages the input signal to determine the output is known as the averaging time. In general, the longer the averaging time, the more accurate the output. Long averaging times for acoustical measurements require lengthy tests. Therefore, the individual must optimize the test time (averaging time) with respect to the accuracy desired.

If a reverberant room is used as the measurement environment, with rotating vanes to improve the diffusivity, the signal level in one frequency band will appear much like the one shown in Fig. 4-7. The

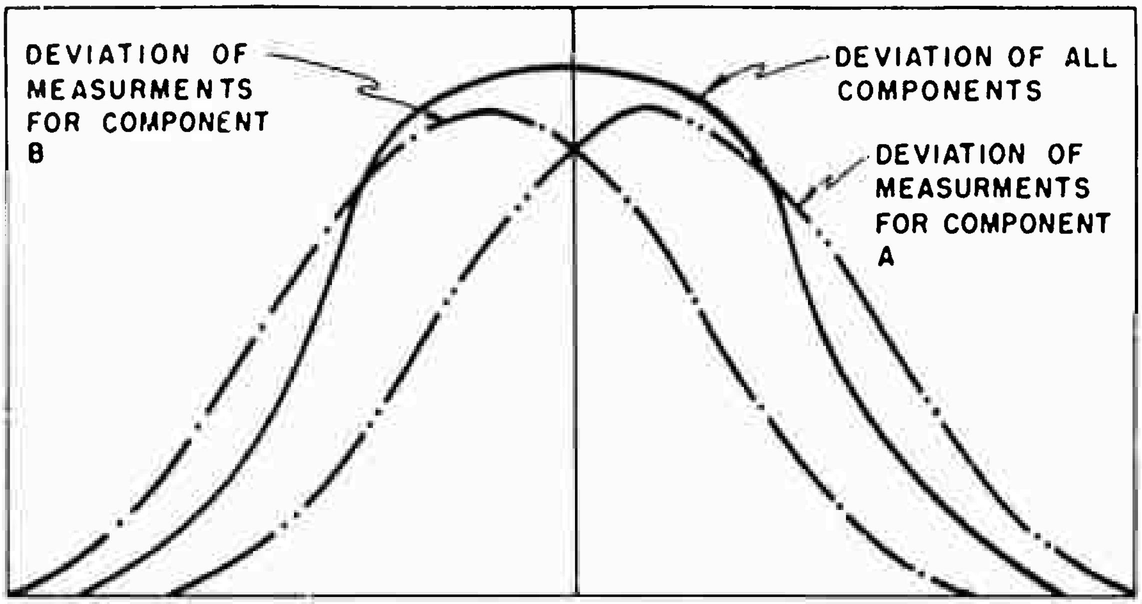


Fig. 4-5. Deviation of Individual Measurements too Great to Provide Distinction.

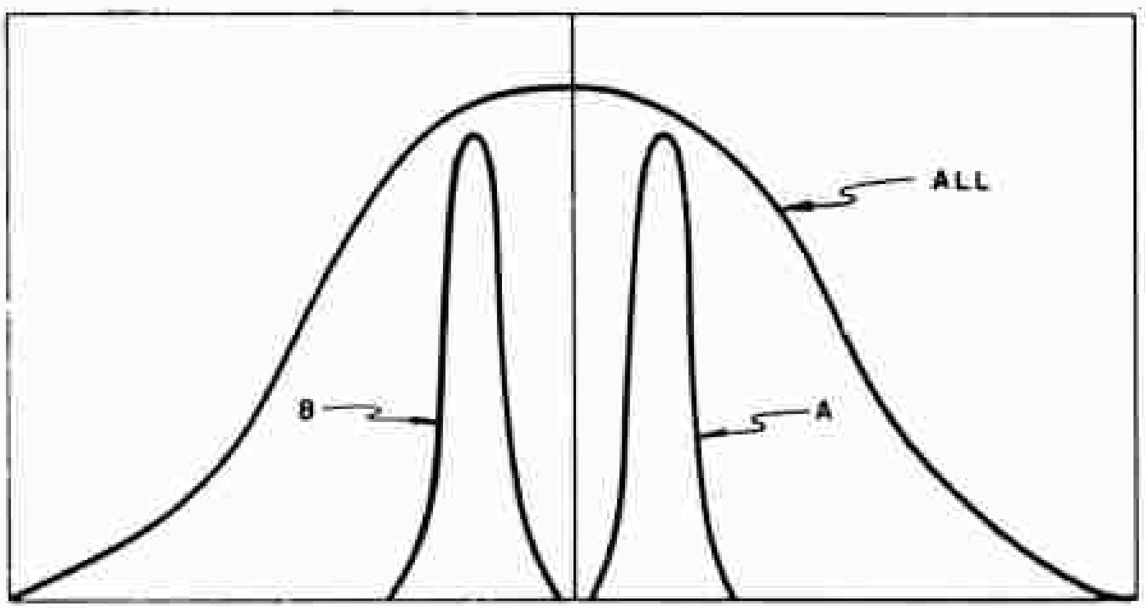


Fig. 4-6. Deviation of Individual Measurements Small Enough for Component Distinction.

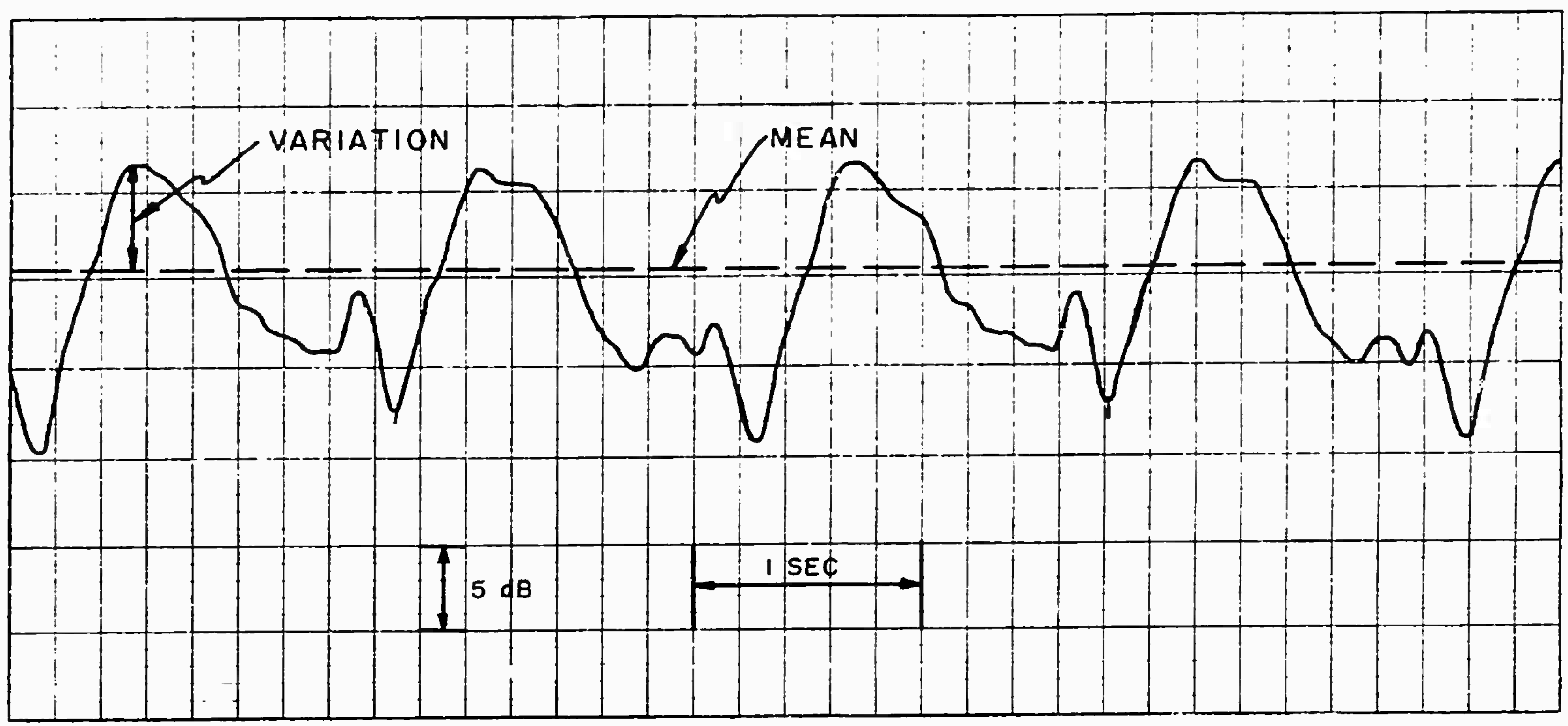


Fig. 4-7. Variation of Sound Level in Reverberant Room With Acoustical Diffusers (Vanes) in Operation.

variation in the signal level shown is a result of the variation of the source and the variation in the sound level at the microphone face due to the rotation of the vanes. The rotating vanes cause the standing waves in the room to move across the face of the microphone. The variation of the signal level from the mean demonstrates the error that can be obtained with measurements taken in a reverberant room without the vanes present. The instrumentation must average this signal to provide an accurate estimate of the mean. The mean of this signal is the sound level within the frequency band. One general rule is: average for at least one complete cycle of the slowest vane in the measurement field. This rule couples the instrumentation averaging time with the vane speed. Thus, averaging time should be considered in conjection with the selection of proper vane speed to provide maximum diffusion.

Repeatability of Component Measurements Within a Facility

Proper certification of the measurement environment will not insure repeatability of measurements if the source output varies drastically over long periods of time. Also, the certification does not insure that a given component will produce repeatable sound levels. In order to examine the repeatability of component measurements in a certified environment, a test was conducted. A fluid power pump was installed in the reverberant facility. Measurements on this component were made on two consecutive days. The standard deviation of the resultant dBA levels was 0.3dBA. This test shows that excellent repeatability can be obtained on a dBA basis.

Repeatability of Measurements Between Facilities

Absolutely no data is available from the fluid power industry to indicate how repeatably a component can be measured by more than one facility. Without a knowledge of the repeatability that can be expected between acoustical measurement facilities, comparison of the data produced by these facilities is impractical.

The Fluid Power Research Center has proposed a measurement survey which will provide the necessary data to indicate the practicability of the comparison of sound level measurements taken in different fluid power laboratories. The survey is divided into two phases. Phase I will be the measurement of the electronic acoustical reference source discussed in Appendix D. The data acquired from the measurement of this source will indicate how repeatably different facilities can measure a source that is not affected by the fluid power support system. Phase II will be the measurement of a given fluid power component and will indicate what effects the fluid power support system has on the repeatability between laboratories.

Conclusions

The implementation of the recommendations presented in this section

can provide accurate and repeatable sound power measurements of fluid power components. Some type of facility certification must be conducted to verify the repeatability of measurements within a facility. Data must also be obtained that indicates the repeatability that can be expected from measurements in different laboratories.

- ISOLATING COMPONENT NOISE -

There are several variables introduced into the measurement environment by the support system necessary to operate a hydraulic pump. These variables include: airborne drive shaft noise, structureborne drive shaft noise, fluid conduit noise, pump mount noise, drive support noise, and load valve noise. In order to document the variation which can typically occur because of these factors, several experimental results are presented below. During the tests discussed in the following paragraphs, only one variable was changed at a time.

Airborne Drive Shaft Noise

A pump test was conducted without a cover over the drive shaft supplying power to the pump. Afterwards, a cover was installed over the drive shaft and taped to the pump mount and wall of the test chamber. Table 4-3 shows that the variation in measurements which occurred was 2.1dB in total sound power and 3.1dBA in total "A" weighted sound power.

Structureborne Drive Shaft Noise

In one test facility, it was determined that the drive shaft was transmitting an unusual amount of structureborne noise to the pump. This occurred because the drive shaft was supported externally by a bearing which was mechanically coupled to the power supply (Fig. 4-8). Although a flexible coupling was located between the power supply and the drive shaft, the same mount held the power supply and a drive shaft bearing. A rigid coupling was used to connect the pump to the drive shaft. It was extremely difficult to isolate the problem because when the background measurements were made in the conventional manner of disconnecting the pump at the drive shaft in the room, the structureborne path was also severed. Once the problem was isolated and the bearing uncoupled from the power supply, a decrease of 5.8dBA was observed in the measured apparent sound power level for the pump under test. Table 4-4 shows the results of the tests before and after modification of the drive system.

Fluid Conduit Noise

Controlled measurements were made of a pump and the support system with the fluid conduits to the pump uncovered. Each of the fluid lines to the pump was covered individually and a measurement made after each modification. Table 4-5 shows the changes that resulted in total dBA

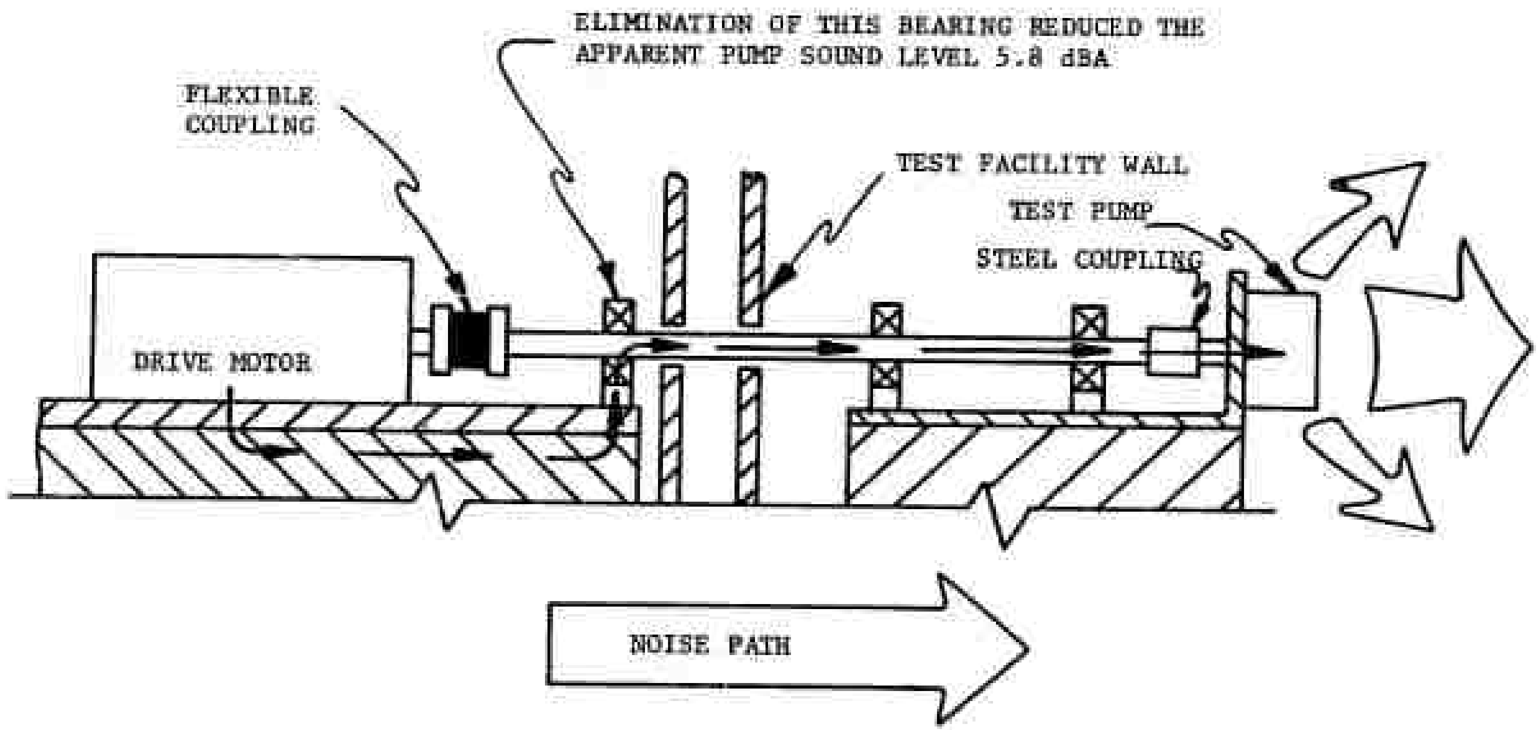


Fig. 4-8. Cross-Section of Drive System That "Short-Circuited" Structureborne Noise to Pump.

TABLE 4-3

Effects of Drive Shaft Cover.

Test Condition	Sound Power Level	
No Cover	93.1dB	91.5dBA
With Cover	91.0dB	88.4dBA

TABLE 4-4

Effects of Structureborne Drive Shaft Noise.

Test Condition	Sound Power Level
Before Modification	85.4dBA
After Modification	79.6dBA

TABLE 4-5

Effects of Wrapping Fluid Lines.

Test Conditions	Sound Power Level
Before Wrapping Lines	90.3dBA
After Wrapping Suction Line	88.8dBA
After Wrapping Suction & Outlet Lines	85.5dBA

after the fluid conduits in the measurement environment were wrapped with a layer of foam rubber covered with leaded vinyl. The total decrease in sound level with the fluid line treatment was 4.8dBA.

Pump Mount Noise

Pump mount noise can be reduced two ways. First, the basic construction of the mount can be altered. Second, acoustical material can be placed on the mount to attenuate its sound power output. Table 4-6 shows the results obtained by modifying the mount and covering the mount. Each of these changes was made individually. The total reduction in the "apparent" sound level of the pump was 2.6dBA.

Drive Support Noise

Acoustical treatment was used to cover the support for the pump drive in order to minimize the background effects due to the support and the fluid lines embedded in the support. Table 4-7 shows that this treatment produced a total reduction of 3.3dBA. The treatments for drive support noise and pump mount noise were accomplished in sequence with only one change being made at a time. The total reduction due to these treatments was 5.9dBA, which means that approximately four times as much power was coming from the untreated portions of the support system as was emanating from the pump.

Load Valve Noise

In some facilities, it is tempting to install the load valve for the pump in the test environment. Table 4-8 shows that, in one instance, removing the load valve from the test environment dropped the measured sound power level by 4.0dBA. Although a load valve could be acoustically treated, it is recommended that the number of circuit components in the test environment be minimized.

It is apparent, after considering the results of the tests reviewed in this section, that the measurement of a background for correcting the measured sound level of a pump is a critical part of the proposed test procedure.

- BACKGROUND MEASUREMENTS -

The current industrial recommended procedure for the measurement of fluid power component noise suggests the measured sound power level of a pump (L'_p) be corrected by subtracting a background measured with the drive disconnected. The background is subtracted, in the proper manner, from the measurement of the component to obtain the actual sound power level. This method corrects for noise generated by sources unrelated to the fluid power system in the measurement environment and

TABLE 4-6

Measurement Variations Due to Mount Configuration and Covering Mount.

TOTAL SOUND POWER (dBA)		
Conditions	Mount w/Braces	Mount w/o Braces
Mount Covered	85.4	84.6
Mount Uncovered	87.2	86.3

TOTAL SOUND POWER (dB)		
Conditions	Mount w/Braces	Mount w/o Braces
Mount Covered	88.7	86.3
Mount Uncovered	88.6	86.0

TABLE 4-7

Noise Reduction Due to Acoustically Treating Drive Support.

Test Condition	Sound Power Level	
Support Untreated	84.6dBA	86.3dB
Support Covered	81.3dBA	83.9dB

TABLE 4-8

Noise Reduction Due to Taking Load Valve Out of Test Environment.

Test Condition	Sound Power Level
Valve in Room	84.5dBA
Valve Removed	80.5dBA

noise transferred into the environment from outside. If the facility has been verified, the corrected sound level is an accurate measurement of the pump, fluid lines, pump mount, and other variables. If the noise produced by the liner or the pump mount or both of these sources is greater than the noise produced by the pump, the sound power level obtained is an accurate measurement of something other than the pump. In this case, the actual sound power level of the pump is less than the measured level. If the sound emitted from the extraneous sources mentioned is considerably less than the sound radiated from the pump, the sound power level obtained by correcting with the disconnected drive method is equal to the actual sound power of the pump. A maximum level (L_{max}) will be obtained by subtracting the sound power level obtained in the measurement facility, while the drive to the pump is disconnected (L_d) from the sound power level obtained in the measurement facility while the drive to the pump is connected (L'). The actual sound power level of the pump (L_p) is less than or equal to the level obtained (L_{max}). Then:

$$L_p \leq L_{max} = L_p' - L_d \tag{4-1}$$

A second proposed method for measuring the sound power output of a pump suggests that the sound power level measured for the component (L_p') be corrected by subtraction of the sound power level (L_B) obtained by covering the pump with a "box" (acoustical isolator). If the "box" is a perfect acoustical isolator, all noise that is not directly radiated into the "box" will be accounted for during the subtraction of the two levels:

$$L_p = L_p' - L_B \tag{4-2}$$

Assuming that only pump noise enters the "box" the resultant level (L_p) will be the actual sound power level of the pump.

Conversely, if the "box" is not a perfect acoustical isolator, some of the noise radiated from the pump will be measured during the time the "box" is installed. The corrected result would be a sound power level which is less than the actual sound power of the component.

Subtraction of the sound power level obtained, in the measurement facility, while a "box" is isolating the noise radiated from the pump; from the measured sound power of the pump, yields a minimum level (L_{min}) for the actual sound power of the component:

$$L_p \geq L_{min} = L_p' - L_B \tag{4-3}$$

where (L_p) is the actual sound power level of the pump.

If both of the methods that have been discussed are used during

the measurement of a component, the actual sound power level of the component will be bounded on both sides. Then:

$$L_{min} \leq L_p \leq L_{max} \tag{4-4}$$

where: L_{min} was obtained with the "box" method, and L_{max} was obtained using the drive disconnecting method.

The suggested "bracketing" procedure was applied to a pump at OSU. The results are shown in Table 4-9.

TABLE 4-9

Results of Bracketing Procedure.

Background Used for Calculations	Sound Power
Disconnecting Drive Shaft	81.2dBA
Covering Pump	79.1dBA

From the previous discussion, it may be concluded that the actual sound power (L_p) of OSU-SP-12 is greater than or equal to 79.1dBA and less than or equal to 81.2dBA.

$$79.1 \leq L_p \leq 81.2 \tag{4-5}$$

It is reasonable to assume that the "box" is not a perfect acoustical isolator. Then (L_p) will be greater than 79.1dBA. It is also reasonable to assume that the background noise produced by the fluid lines and pump mount have an increasing effect on the sound level measurement of the pump. Disconnecting the drive shaft and correcting the pump sound power does not account for noise produced by sources other than the pump. Then, the actual sound power of the pump is less than 81.2dBA, and:

$$79.1 < L_p < 81.2 \tag{4-6}$$

The use of both correction methods in a certified test facility provides known limits for the sound power level of a component.

CHAPTER V

PUBLISHED NOISE LEVELS OF FLUID POWER PUMPS

One manner in which the noise levels of commercially available hydraulic pumps can be surveyed is to review noise levels reported by component manufacturers. Values of the airborne pump noise are frequently published in magazines and advertisement literature. Project personnel were unable to find any advertised values of structureborne or fluidborne noise for hydraulic pumps. Published sound levels for fluid power pumps are presented in this report to provide a reference to which the results of the experimental measurements can be compared.[1]

The sound levels included in this chapter are from two sources. Several of the sound levels were reported in national publications. Some of the sound levels were reported to the Fluid Power Research Center by participants in a measurement survey. In general, these levels were obtained by various procedures in different environments. It is assumed, where it was not specified, that the reported sound pressure level is the level which would occur at three feet from the source in a free-field above a reflecting plan (hemispherically divergent environment).

Table 5-1 is a summary of the survey results. To minimize the number of variables, sound levels were selected for the same operating speed, 1800 rpm, and the same pressure, 103.5 bar. The resultant sound levels can be plotted as a function of horsepower, knowing that the pressure and speed are approximately the same.

Figs. 5-1 and 5-2 graphically display the results of the survey. The number of occurrences of a given level is plotted versus the level in Fig. (5-1). It can be seen that the majority of the reported levels are between 79dBA and 83dBA. The levels vary from 61dBA to 83dBA, a range of 22dBA.

The sound pressure levels versus pump horsepower are plotted in Fig. 5-2. Although pump types are known, it was not possible to observe any definite trends as a function of basic pump design, i.e., gear, vane, or piston. It is known that pumps G and H were tested in the same laboratory, using the same test method. It is reasonable to assume that the majority of the remaining pumps (A-F) were tested in the U. S. using essentially the same procedure but different environments.

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[1] A more complete discussion of this information can be found in Ref. [5].

TABLE 5-1.

REPORTED MAXIMUM SOUND LEVELS FOR VARIOUS PUMPS

PUMP	SPEED (RPM)	PRESSURE (bar)	FLOW (LIT/MIN)	SOUND LEVEL (dBA)
A	1800	103.5	87.2	79
B	1800	103.5	183.7	82
C	1800	103.5	238.5	83
D	1760	103.5	189.5	82
E	1790	103.5	56.8	79
F	1790	103.5	13.5	74
G	1800	103.5	24.2	65
H	1800	103.5	24.2	61

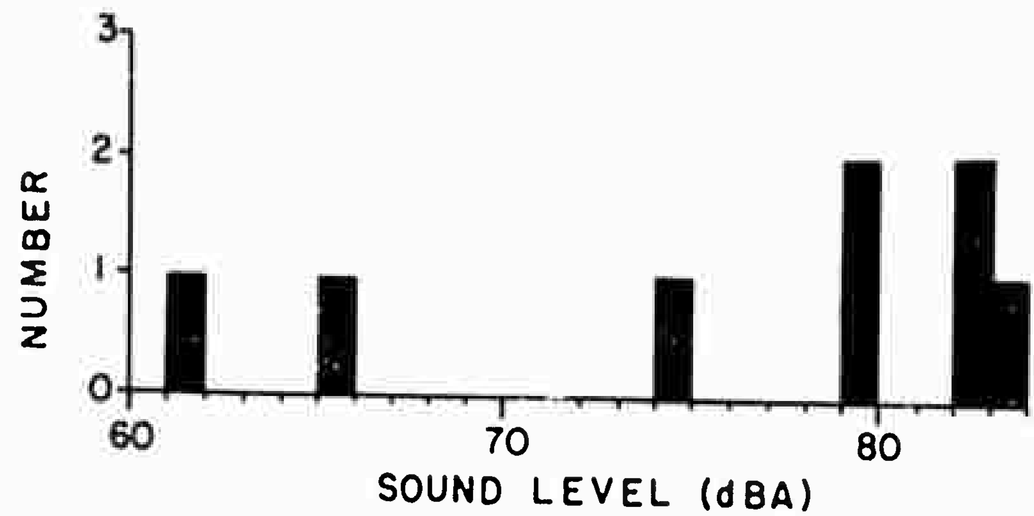


Fig. 5-1. Frequency Plot for Pumps in Table I.

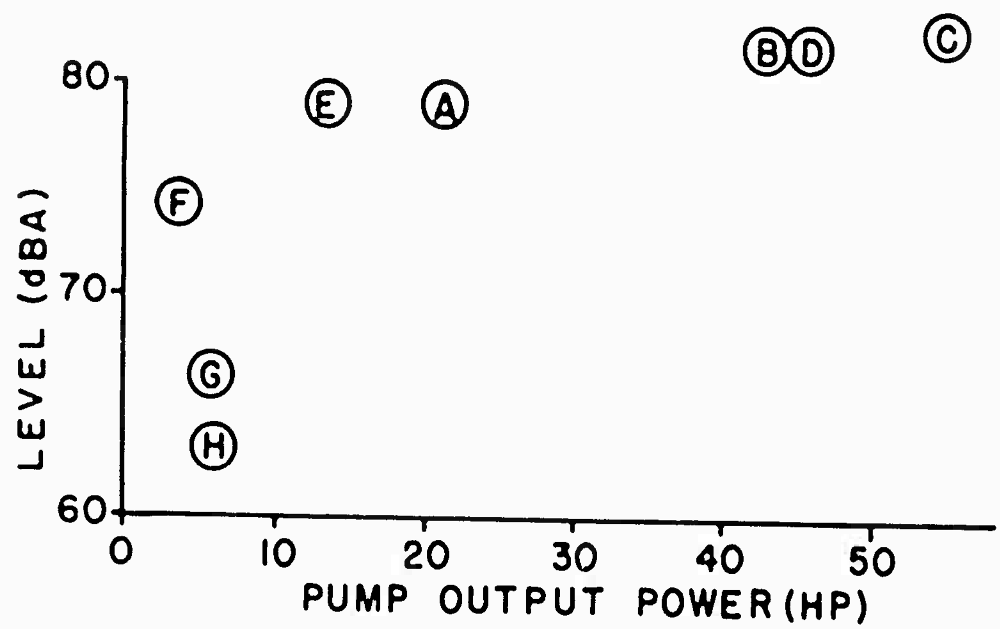


Fig. 5-2. Sound Levels Versus Pump Output Power (From Table I).

The results of the survey of published sound level data can be compared with the experimental measurements of sound levels presented in the following chapter.

CHAPTER VI

EXPERIMENTAL SURVEY OF NOISE LEVELS FOR FLUID POWER PUMPS

The objective of this phase of the project is to establish the airborne sound power levels of several fluid power pumps. The results of an accurate experimental survey of the sound power levels of commercial hydraulic pumps will aid in establishing the realistic limits for specifications. The prediction of fluid power system noise will be enchanced if the variations in pump sound level as a function of pressure and speed are available.

The experimental survey required first establishing a repeatable measurement procedure. A procedure was developed as reported in Chapters II and III. Project personnel are confident that repeatable results are being obtained. The measurement results presented in this chapter represent only a portion of the measurements that will be made. Remaining measurements will be conducted according to the same procedure used to obtain the results presented in this chapter. Complete results of the survey will be presented in a subsequent report.

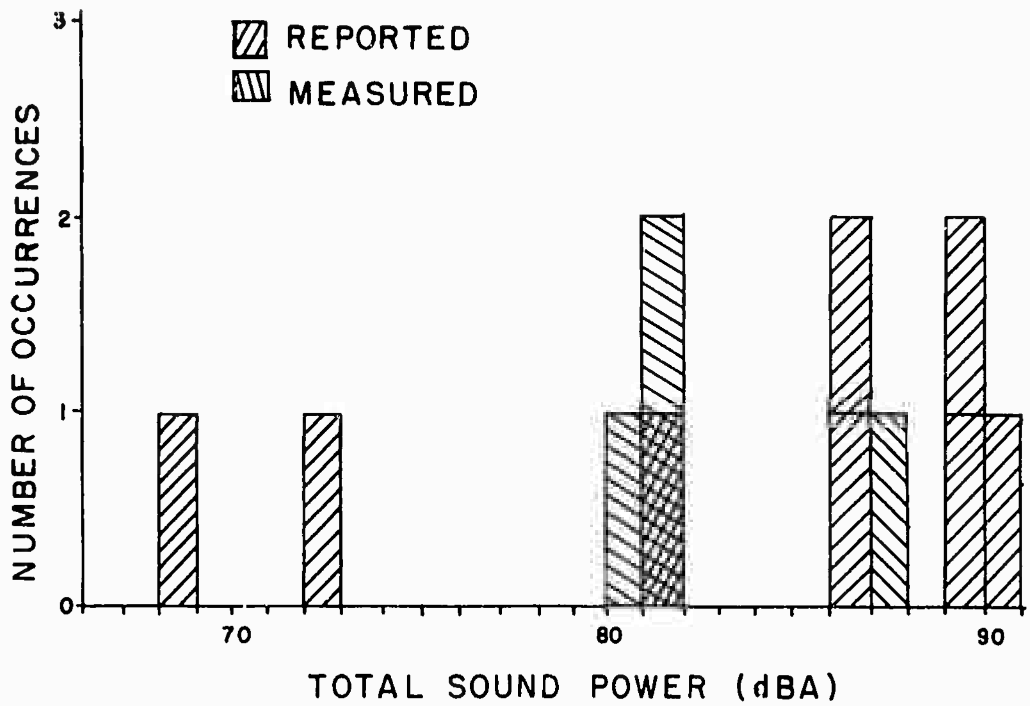
Table 6-1 lists the total sound power level for each of the units tested. Three test conditions were established. One test condition was 2000 rpm, 2000 psi (138.0 bar). A second test condition was speed 2000 rpm, operating pressure reduced to 200 psi (13.8 bar). For the third test condition the speed was reduced to 600 rpm and the pressure decreased to 60 psi (4.1 bar). The first condition was selected to simulate full speed operation under full load, the second condition was intended to simulate full speed operation with reduced system pressure, and the third condition was requested by some manufacturers to simulate idle operation. The inlet pressure was maintained at 0 psi for three of the four units. One fixed displacement unit has excessive outlet pressure fluctuation with zero inlet pressure. For this unit the inlet pressure was set a 2 psi. The test temperature was 65.5 degrees C. for the "full load" test. For the reduced horsepower tests the temperature was maintained at 38 degrees C.

In Fig. 6-1 the results of the measurement survey are compared with the reported levels presented in Chapter V. The test pumps include a piston unit, two external gear pumps, and a vane pump. With the exception of the piston unit the controlled measurements appear to be about 6dBA lower than the published sound power levels. In view of the fact that the controlled measurements were taken at 2000 rpm (instead of 1800 rpm) and 2000 psi (instead of 1500 psi), the generally lower sound levels at the same horsepower are somewhat surprising, assuming the published values are accurate.

TABLE 6-1

EXPERIMENTAL TEST RESULTS TOTAL SOUND POWER

PUMP (OSU-NP)	SPEED (RPM)	PRESSURE (BAR)	FLOW (LIT/MIN)	SOUND POWER (dBA)	PUMP POWER (HP)
10V	2000	138.0	87.1	80.4	26.9
11GE	2000	138.0	98.0	81.2	30.2
12GE	2000	138.0	97.6	81.2	30.1
13P	2000	138.0	93.9	87.6	29.0
10V	2000	13.8	101.4	76.2	3.1
11GE	2000	13.8	113.6	75.2	3.5
12GE	2000	13.8	107.9	72.2	3.3
13P	2000	13.8	90.1	79.0	2.8
10V	600	4.1	≈30.4	54.3	.28
11GE	600	4.1	≈34.1	62.3	.31
12GE	600	4.1	≈32.4	57.4	.30
13P	600	4.1	≈27.0	62.9	.25



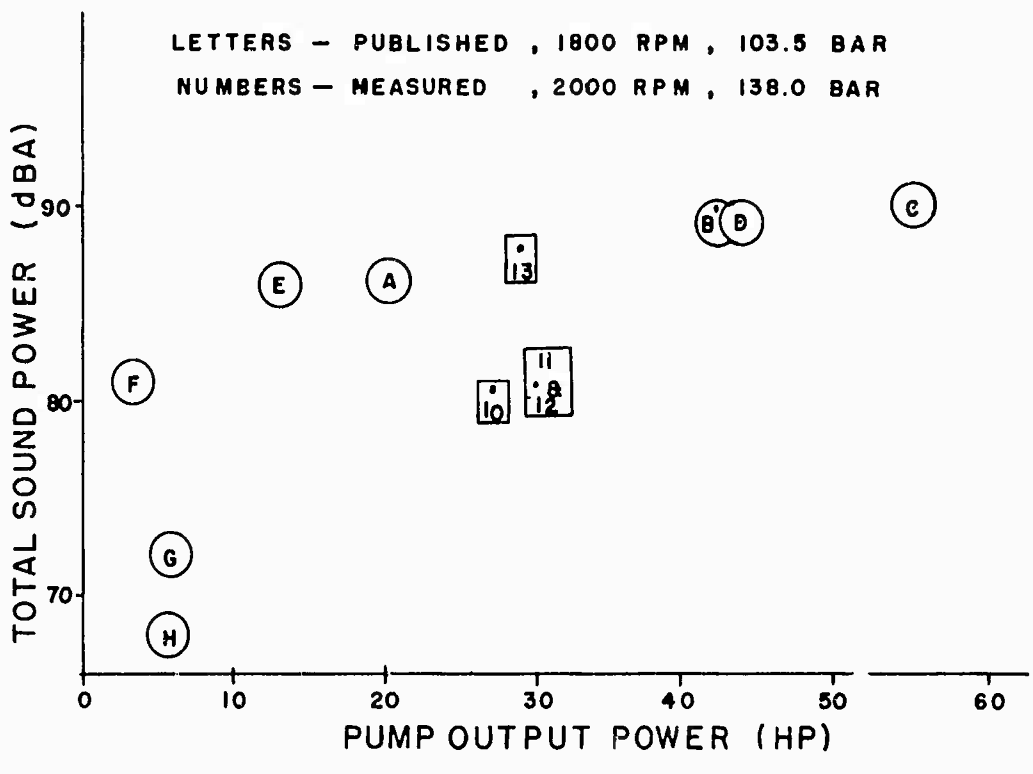


Fig. 6-1. Comparison of Measured and Reported Sound Levels on Two Different Graphs.

More data acquired under controlled conditions will be needed to make any definite conclusions but so far indications are that the published sound levels are too high. If this is true, it is consistent with the philosophy of some pump manufacturers. Certain component manufacturers have indicated that it is acceptable to report a sound level higher than the actual level of the component. This approach is reflected in the test code discussed in Chapter I.

The measurements shown on the graphs in Fig. 6-1 are total sound power level. To convert these total sound levels to an equivalent pressure level three feet from the source in a free field above a reflecting plane, 7dBA should be subtracted from the values shown. The latter reference to sound pressure level is frequently used for reporting airborne noise.

General trends for the change of the sound power of a pump can be seen on Fig. 6-2. The graph of Fig. 6-2 shows the relative change of sound power of a component for varying speed and pressure. The data from Table 6-1 is plotted in Fig. 6-2 to produce a rough indication of the slopes (or sensitivities) of sound power output versus speed and pressure changes.

The importance of fluidborne noise was discussed in Chapter IV and other chapters. The results of fluidborne noise measurements made during the survey are presented in the following chapter.

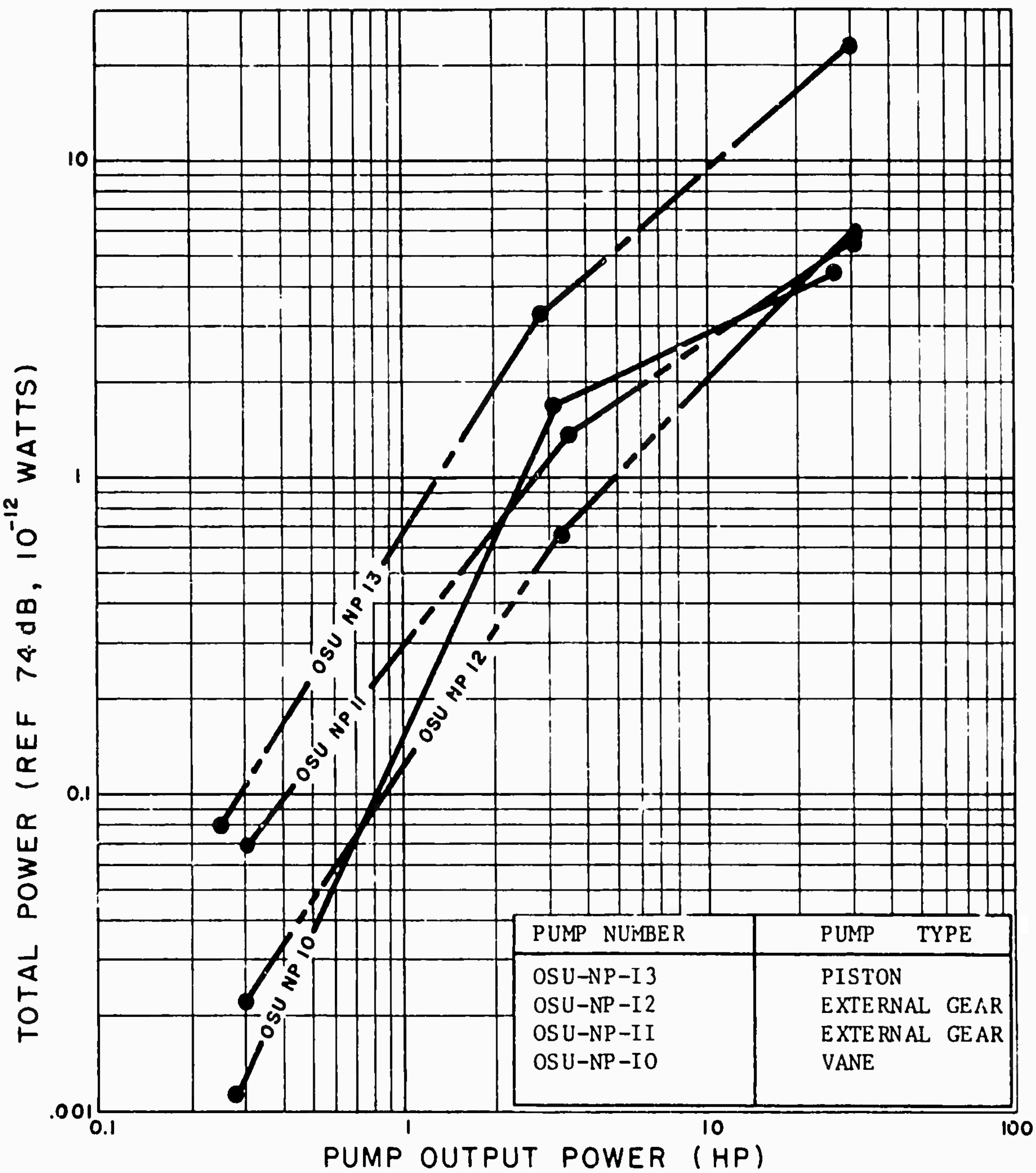


Fig. 6-2. Plot of Measured Sound Levels Versus Pump Output Power.

CHAPTER VII

EVALUATION OF FLUIDBORNE NOISE

Pressure pulsations within a fluid power system provide the potential for increased system sound levels. At the present time, no standard procedure exists for the measurement of fluidborne noise. The measurement procedure presented in Appendix H is a first draft of a fluidborne noise test method. It can be used as a guide for the measurement of fluidborne noise. It will not guarantee repeatible results if any parameter other than the component being tested is changed.

- FLUIDBORNE NOISE MEASUREMENTS -

A series of fluidborne noise measurements has been initiated at OSU. A modification of the test procedure presented in Appendix H has been implimented for this series of tests. Procedural errors are minimized by maintaining both the measurement and fluid power systems in the same configuration for each test. The component under test is the only parameter that is changed. The results for two pumps, OSU-NP-10 and OSU-NP-13, are shown in Fig. 7-1. For purposes of identification, OSU-NP-10 is a vane pump, and OSU-NP-13 is a piston pump. The piston pump has significantly higher fluidborne noise levels. The data indicates that in the same system the vane pump would produce lower fluidborne noise levels than the piston pump.

The same recording instrumentation was used for both airborne and fluidborne noise measurements. The pressure transducer for fluidborne noise measurements is a Piezotronics crystal pressure transducer and power supply. The piezo transducer affords the possibility of high frequency pressure pulsation measurement in fluid power systems. The transducer may be inserted directly into the fluid system, therby reducing considerations of dynamic coupling of the transducer to the system. As indicated previously, the pressure data is analyzed using a 1/3 octave band analyzer.

- DATA REDUCTION -

The 1/3 octave analysis is reduced with the aid of the computer and the program presented in Appendix E. A sample output from the computer is shown in Table 7-1. An explanation of the output terms is provided in Table 7-2.

Reported pressure levels are referenced to 20 $\mu N/m^2$. This procedure

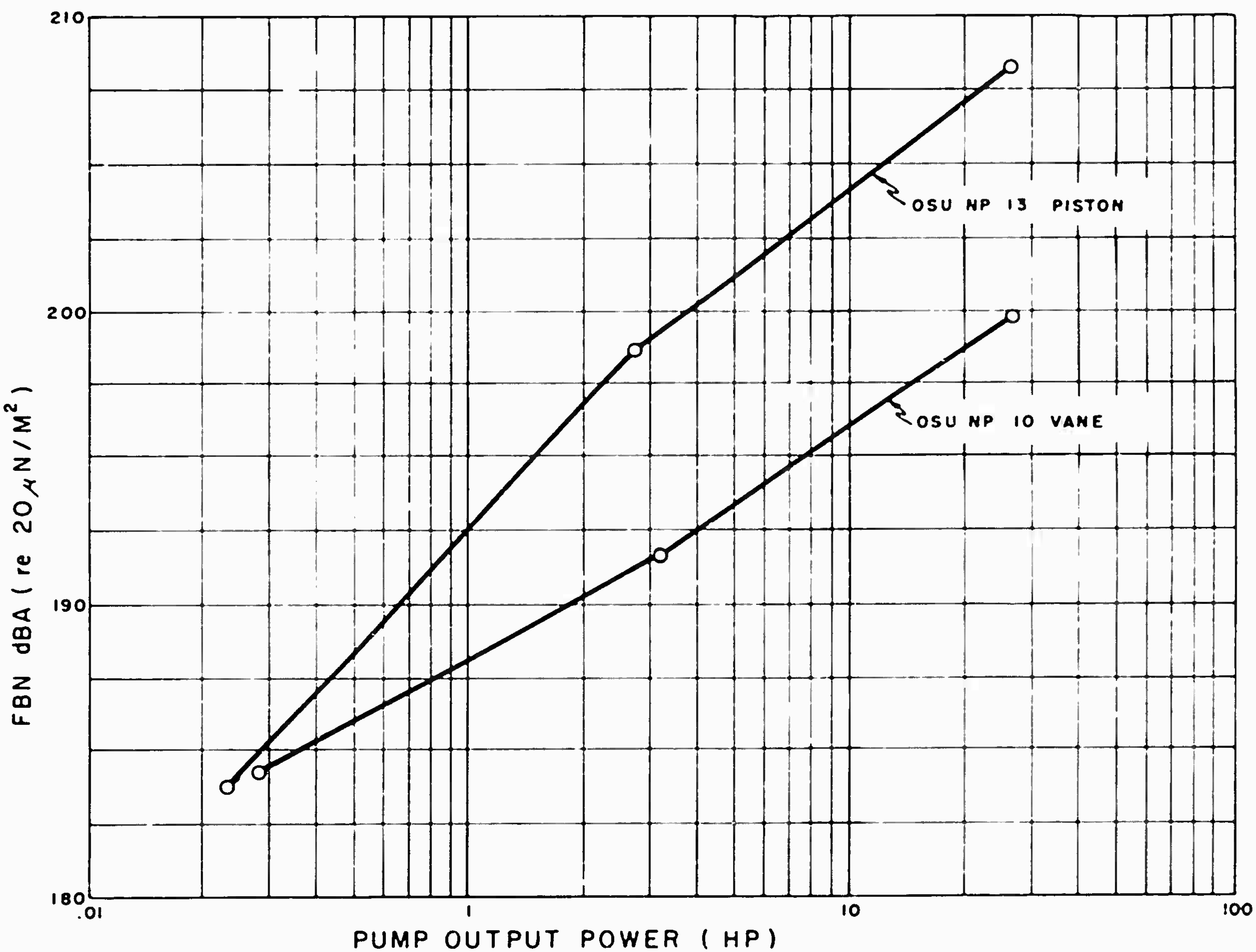


Fig. 7-1. Fluidborne Noise Versus Pump Output Horsepower

TABLE 7-1. SAMPLE FLUIDBORNE NOISE COMPUTER OUTPUT

OSU-FPRC
ACOUSTICS LABORATORY DATA LOG

FREQ	PRESS	BKG	CORR	"A"	POWER	REL-20	FREQ
100.	52.00	46.50	50.56	31.46	0.0001	155.46	100.
125.	57.50	46.20	57.17	41.07	0.0005	165.07	125.
160.	52.20	51.50	43.93	30.73	0.0000	154.73	160.
200.	59.10	52.50	58.03	47.23	0.0021	171.23	200.
250.	74.30	45.00	74.29	65.69	0.1477	189.69	250.
315.	72.50	49.60	72.48	65.98	0.1577	189.98	315.
400.	60.90	39.00	60.87	56.07	0.0161	180.07	400.
500.	57.80	39.00	57.74	54.44	0.0111	178.44	500.
630.	73.70	39.00	73.70	71.80	0.6024	195.80	630.
800.	64.30	39.00	64.29	63.49	0.0889	187.49	800.
1000.	62.20	39.00	62.18	62.18	0.0658	186.18	1000.
1250.	62.90	39.00	62.88	63.38	0.0867	187.38	1250.
1600.	63.00	39.00	62.98	63.98	0.0996	187.98	1600.
2000.	60.90	39.00	60.87	62.07	0.0641	186.07	2000.
2500.	58.80	39.00	58.75	59.95	0.0394	183.95	2500.
3150.	60.10	39.00	60.07	61.27	0.0533	185.27	3150.
4000.	54.20	39.00	54.07	55.07	0.0128	179.07	4000.
5000.	43.50	39.00	41.60	42.10	0.0006	166.10	5000.
6300.	42.50	39.00	39.93	39.73	0.0004	163.73	6300.
8000.	42.30	39.00	39.56	38.46	0.0003	162.46	8000.
10000.	43.90	39.00	42.20	39.80	0.0004	163.80	10000.

TOTAL PRESSURE --------------- 79.17 DB
"A" WEIGHTED PRESSURE ------------------ 75.61 DBA
TOTAL "A" WEIGHTED POWER -------------------------- 1.4499
"A" WEIGHTED PRESSURE RELATIVE TO 20 MN/M**2 ---------------- 199.61 DBA

SYSTEM PARAMETERS FOR OSU-NP-10
PRESSURE=2000PSI INLET=0PSI SPEED=2000RPM FLOW RATE=23.0G TEMPERATURE=65.5C

TABLE 7-2

LISTING OF TERMS USED IN FLUIDBORNE DATA OUTPUT

Column Heading	Parameter
FREQ	1/3 octave center frequency
PRESS	dB levels in 1/3 octaves for pressure analysis
BKG	1/3 octave analysis of system background noise
CORR	corrected pressure (i.e. PRESS - BKG)
"A"	dBA weighted pressure in 1/3 octave bands
POWER	power associated with dBA weighted pressure
REL-20	dBA weighted pressure relative to 20 $\mu N/m^2$

is a deviation from normal high frequency fluid pulsation analysis. Fig 7-2 depicts graphically why the same reference is used for both fluidborne and airborne noise measurements. The use of a common reference allows the comparison of fluidborne and airborne noise with conventional units. The conversion from the measurement units to 20 $\mu N/m^2$ is a function of the pressure transducer and analyzer used. For the data presented in this report, the conversion is 124.0dBA. Fig. 7-3 may be used to obtain "peak to peak" pressure ripple (i.e. fluidborne noise) for any 1/3 octave band or the total spectrum. The scaling of the axes of the pressure versus dB graph is a function of the measurement system. Hence, Fig 7-3 is not applicable for all fluidborne noise measurements.

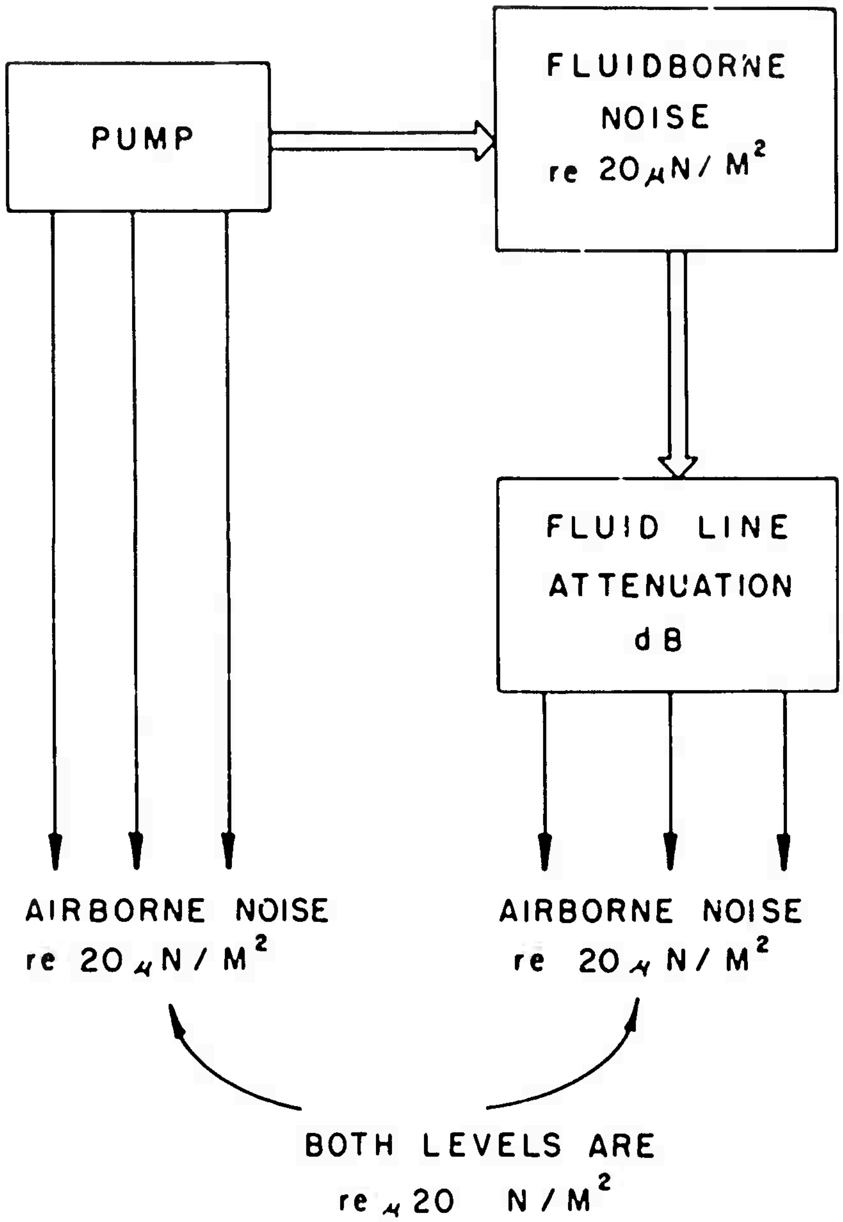


Fig. 7-2. Relationship Between Airborne And Fluidborne Noise Measurements Referenced To Same Levels.

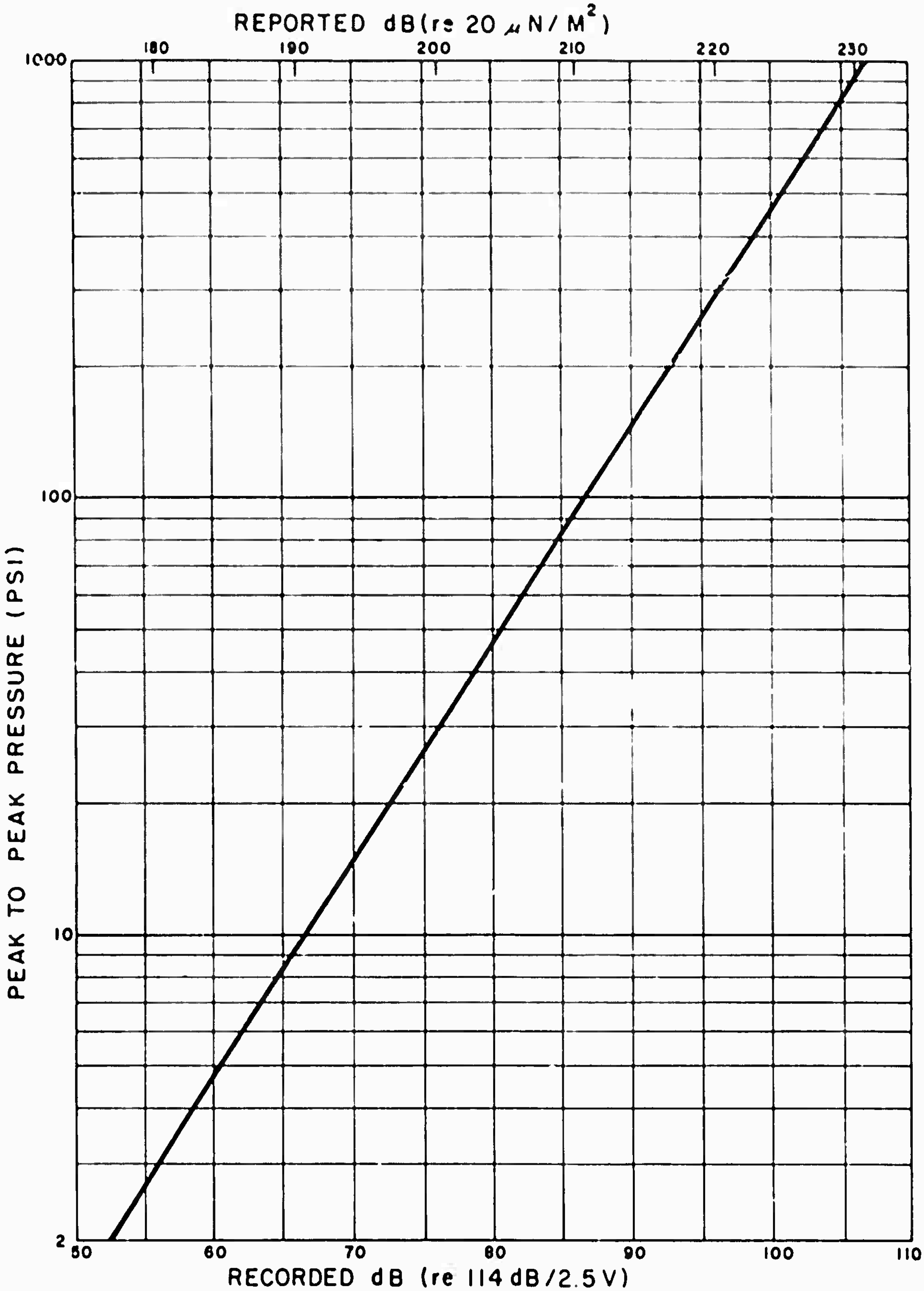


Fig. 7-3. dB vs. Peak to Peak Pressure.

CHAPTER VIII

GENERAL DISCUSSION

Two project objectives are discussed in this report. The first objective was the development of noise measurement test methods. The second objective is the acoustical measurement of selected fluid power components.

This report concludes the noise test method development effort covered by this contractural agreement. The objective of measuring component noise is scheduled to continue through May 1973. Both of these objectives will assist in establishing realistic noise specifications for fluid power components.

The following paragraphs of this chapter discuss various aspects of the two project objectives. A complete listing of conclusions and recommendations is included in chapters reserved for those subjects.

- TEST METHOD DEVELOPMENT -

The objective of developing noise measurement test methods was originally scheduled as a minor effort for this contract year. Two circumstances necessitated that it become a major effort. First, the industry formed a Tri-Level Conference (NFPA, ANSI, USTAG) to make specific recommendations to ISO regarding the measurement of airborne noise from pumps. Second, the measurement of airborne noise emitted by selected components could only be meaningful if the measurements were based on the best test method available.

Project personnel contributed fully and openly to the efforts of the Tri-Level Conference. Three of the four rough drafts considered by the Conference and the final drafts were written by project personnel. The approved test methods that resulted from the Conference are the basis for all noise measurements being made in the FPRC Acoustics Laboratory.

The consensus of the Tri-Level Conference participants was that the Airborne Test Method represented the best guidance available. The Conference participants who had helped in the development of the earlier NFPA test methods for pumps and motors agreed that significant improvements were incorporated into the Conference recommendations.

A test method for measuring fluidborne noise was introduced at the Conference by Project personnel. The urgency of completing the airborne test method precluded extensive development of the fluidborne test method. There was general agreement among participants that a test method for mea-

suring fluidborne noise was needed. Although specific guidance for the fluidborne test method was sought, only general comments about the need for such a document and the difficulties involved were discussed.

The evaluation of the airborne test procedure shows that the important test system parameters are considered in the Recommended Airborne Test Method. It also shows that the guidance regarding those system parameters are inadequate to insure reasonable repeatability. Over 5dBA sound power reduction was obtained by treating only the mount and drive support for one test. In another set of tests on one unit, over 4dBA reduction in total sound power was obtained by treating only the fluid lines.

There was not time available to completely evaluate the fluidborne test method. The present method being used to evaluate fluidborne noise parallels the recommended test method. Presently all of the system parameters are held constant between tests, the only major variable being the pump under test. The results of four measurements of the fluidborne noise associated with one pump yielded a sample standard deviation of less than ½dBA.

There are no known industrially approved test procedures for the measurement of structureborne noise. Structureborne noise measurements were obtained, in certain instances, to assist in isolating airborne noise sources in the test environment. These measurements of structureborne noise were not taken according to any particular procedure or test method. Structureborne noise represents another aspect of fluid power component noise that warrants investigation.

- COMPONENT NOISE MEASUREMENT -

Accurate measurement of the airborne noise emitted by fluid power components is dependent on the complete isolation of all noise sources in the test environment except the test unit. Since the perfect isolation of the test system associated with a component is not practical, the resultant airborne noise measurement for a component represents an upper limit of the actual sound power level of the unit. Before proceeding with airborne measurements of fluid power pumps, each possible source of error was considered and minimized.

Once a treatment method was obtained for a given source of airborne noise, the same treatment was used during each subsequent measurement. The only major variable between airborne noise measurements was the test unit.

The remainder of the fluidborne noise measurements, which are to be taken for this project, will be made keeping as many system parameters constant as possible. If fluidborne test methods are investigated, and it becomes apparent that the measurement process can be improved, then the new method will be utilized.

Structureborne measurements will be made on selected components. The procedure for these measurements will be recorded. But, it is not anticipated at this time that a parametric study will be conducted in conjunction with these measurements.

The test methods used for the component noise measurements will be recorded in the final report on this contractual agreement.

The two operational difficulties associated with the measurement objective of this project have been: 1) the lack of verified test methods, and 2) the one pump specifically selected by Project Monitors for noise measurements has an output flow rate which required major changes in the facility support system. Neither of these difficulties has created any major problems. Project personnel are confident that the objectives of this phase of the project can be met by the end of May 1973, which is the scheduled completion date.

CHAPTER IX

CONCLUSIONS

The conclusions outlined in this chapter are a summary of the major conclusions resulting from this project to date. Thus, the conclusions resulting from the noise measurement test method development effort and the actual noise measurement effort are included in this chapter. The conclusions are divided into the three categories of fluid power component noise: airborne, fluidborne, and structureborne.

- AIRBORNE NOISE -

The procedure developed by the Tri-Level Conference on Noise in Fluid Power Systems can be considered to represent the most recent industrially endorsed measurement test method for airborne noise emitted by fluid power pumps. It is reasonable to expect that, since it is based on acoustically valid test method, the measurement accuracy will be reasonable. This means that the measurements will be an accurate indication of the sound power in the environment, which may include more than just the test unit. In order to achieve repeatability between measurement facilities, it will be necessary to more clearly define isolation procedures for support systems.

For any airborne noise measurement test method, it is important to insure: 1) that the measurement facility is verified, 2) that the component being tested is the major source of the noise being measured, and 3) that background levels be taken in such a way that those noises not associated with the test unit can be subtracted from the sound measurements for the test unit.

The technique of measuring a background by rotating the drive shaft while it is not under load is not realistic, since there is no fluid flow and the system is not loaded in the same manner as it is under actual test conditions. The technique of obtaining a background measurement by covering the test unit with an acoustical isolator is very attractive. The use of the isolator combined with the information obtained by disconnecting the drive allows a prediction of the upper and lower limits of the sound power of a component. The acoustical treatment of fluid lines, pump mounts, drive shafts, and other system support elements should be specified in detail in the test method.

Specifying that the background level in dBA must be at least 6dBA

less than the reported component level in dBA can lead to the erroneous assumption that if the difference is greater than 6 dBA then the reported sound level is accurate.

From the point of view of designing a quiet fluid power system it is desirable that the actual sound level of each component be known. There is a tendency for component manufacturers to only show that a given component is below a certain level. Manufacturers should be encouraged to report the sound level of a component as accurately as possible since the system designer would then be able to make confident predictions of the system sound level rather than just being able to predict that the level of the system is less than or equal to a calculated level.

Very little information is available regarding the variation in sound measurements that can be expected between fluid power acoustics measurement facilities.

The pump noise measurement survey being conducted at the FPRC Acoustics Laboratory will yield a comparative set of airborne noise measurements where the only major variable between tests is the unit being measured.

- FLUIDBORNE NOISE -

Fluidborne noise is a significant contributor to fluid power system noise. Not only the results of the airborne test method verification, but other referenced studies have shown that this is true.

The industry is generally aware that an industrially accepted test method for fluidborne noise is needed.

There has not been a major effort within the industry to develop a test method for measuring fluidborne noise.

The most reasonable method for reporting fluidborne noise is to reference it to $20\,\mu N/m^2$, since this reference is compatable for calculating system noise once a transmission loss for the fluid lines is determined.

As with any test method, any recommended test method for measuring fluidborne noise should be supported by actual test results.

- STRUCTUREBORNE NOISE -

This source of noise has received very little published attention by the fluid power industry.

The measurement of structureborne noise can assist in isolating

undesired noise sources in acoustical test environments.

There are no known structureborne test methods accepted by the fluid power industry.

CHAPTER X

RECOMMENDATIONS

Realistic sound level specifications for fluid power components will be based on performance characteristics of the various types of components. For example, the maximum sound level of pumps may be some function of the pump displacement and operating pressure. In the case of fluid lines a minimum reduction of pressure pulses through the conduit walls to the air (a minimum transmission loss) may be the best parameter to specify. Perhaps a maximum level of fluidborne noise can be specified for pumps operating in a verified test system. The following recommendations are based on the results presented in this report coupled with other experiences of project personnel. The recommendations are directed toward reaching two objectives: 1) realistic performance noise parameters and parameter limits for component specifications, and 2) fundamental knowledge that can be used to assist in designing quiet fluid power systems.

1. An airborne test method should be written and submitted to the industry that specifies the isolation techniques to be used for reducing the background noise associated with component noise tests.

2. The results of the controlled airborne noise tests on pumps at the FPRC should be carefully analyzed and coupled to basic theory in order to isolate the critical noise parameters for pumps.

3. A survey of noise test facilities should be conducted to establish the variation within and between laboratories that can be expected in noise measurements within the fluid power industry.

4. Once the variation between laboratories for a reference source is established, a fluid power pump should be used in a survey between laboratories in order to establish the variation that can be expected for actual pump measurements.

5. A practical theory for fluidborne noise needs to be developed and verified. The verification of the theory should lead to a practical test method which would yield accurate and repeatable results. Once a fluidborne test method is developed, the method needs to be used in various labs with a reference source to verify the validity of the method.

6. Basic studies need to be initiated to determine the re-

lative importance of structureborne noise in fluid power systems. Any resultant concepts should be verified experimentally. The verification should be directed toward the development of a realistic test method for structureborne noise in fluid power systems.

7. A systematic method for predicting fluid power system noise needs to be developed. The development of an accurate noise prediction technique would be partially dependent on the successful completion of the studies of airborne, structureborne and fluidborne noise.

8. Inherent in predicting fluid power system noise is the requirement of properly describing the important acoustical characteristics of fluid power conduits. The acoustical characteristics of fluid conduits should be mathematically modeled and experimentally measured.

It is recommended that the modeling and measurement of fluidborne noise be the next major objective for fluid power noise studies. Fluidborne noise is probably the major contributor to fluid power system sound levels. Until the time that fluidborne noise is adequately understood, can be measured practically, and can be confidently predicted and controlled, fluid power systems will plague designers of quiet systems.

APPENDIX A

BIBLIOGRAPHY

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3. NFPA Recommended Standard T3.9.14-1971, "Method of Measuring Sound Generated by Hydraulic Fluid Power Motors." The National Fluid Power Association, Inc. Thiensville, Wisconsin.

4. ISO Recommendation R1680. Test Code for the Measurement of the Airborne Noise Emitted by Rotating Electrical Machinery. July 1970, International Organization for Standardization.

5. BFPR (Basic Fluid Power Research) Annual Report Number 6, September 1972, Section 72-AV, "Acoustics", Oklahoma State University. Stillwater, Oklahoma.

6. ANSI S1.21-19xx, "Proposed American National Standard for the Determination of Sound Power Levels of Small Sources in Reverberation Rooms." American National Standards Institute, New York, N. Y., 10018, February 1972.

7. ANSI S1.2-1962, "Method for the Physical Measurement of Sound." American National Standards Institute, New York, N. Y., 10018, August, 1962.

APPENDIX B

AIRBORNE NOISE COMPUTER PROGRAM

This appendix consists of a listing of the airborne noise computer program discussed in Chapter III. A data listing is provided as well as the control statements and calling program used for loading and executing a Fortran program on the IBM 360 system.

```
//NOISE*** JOB (      ,           ,1),'NOISE',MSGLEVEL=(0,0)
/*ROUTE PRINT RJO
// EXEC FORTGCG
//FORT.SYSIN DD *
      DIMENSION A(21,10),LUB(21,10),LBB(21,10),C(21),B(21),TO(21),
     1VO(21),PO(21),LO(21),POP(21),PP(21),LP(21),CP(21),CO(21),DO(21),
     2DP(21),D2(21),EO(21),EP(21),FP(21),D1(21),B1(21),B1P(21),D1P(21)
     3,GP(21),GO(21),HO(21),HP(21),DAP(21),T1(21),T1P(21),OP(21),OO(21
     4),PO(21),PP(21),RAP(21),QP(21),QO(21),AP(21),RO(21),RP(21),SP(21
     5),SO(21),RAO(21),SOA(21),SOP(21),XP(21),XO(21),R2P(21),
     6R2D(21),R2DP(21),YP(21),YO(21)
      DOUBLE PRECISION A,LUB,LBB,C,B,TO,VO,PO,LO,POP,BP,LP,CP,CO,
     1DO, DP,D2,EO,EP,FP,D1,B1,B1P,D1P,GP,GO,HO,HP,DAP,T1,T1P,OP,OO,
     2PO,PP,RAP,QP,QO,AP,RO,RP,SP,SO,RAO,SAO,SOP,YP,XO,R2P,SPT,DB,
     3TP,DBT,R2D,R2DP,YP,YO
C
C     ----------------------------------------------------
C     THE FOLLOWING 21 NUMBERS ARE THE 1/3 OCTAVE CENTER
C     FREQUENCIES THAT ARE USED IN THIS PROGRAM
C     ----------------------------------------------------
C
      A(1,1)=100
      A(2,1)=125
      A(3,1)=160
      A(4,1)=200
      A(5,1)=250
      A(6,1)=315
      A(7,1)=400
      A(8,1)=500
      A(9,1)=630
      A(10,1)=800
      A(11,1)=1000
      A(12,1)=1250
      A(13,1)=1600
      A(14,1)=2000
      A(15,1)=2500
      A(16,1)=3150
      A(17,1)=4000
      A(18,1)=5000
      A(19,1)=6300
      A(20,1)=8000
      A(21,1)=10000
C
C     ----------------------------------------------------
C     THE NEXT 21 NUMBERS ARE THE SOUND POWER CALIBRATION
C     VALUES SUPPLIED BY RIVERBANK ACOUSTICS LAB.
C     ----------------------------------------------------
C
      A(1,4)=72.0
      A(2,4)=75.5
      A(3,4)=75.5
      A(4,4)=75.5
      A(5,4)=75.5
      A(6,4)=76.0
      A(7,4)=75.0
      A(8,4)=76.0
      A(9,4)=75.5
      A(10,4)=76.0
      A(11,4)=75.5
      A(12,4)=75.5
      A(13,4)=76.0
      A(14,4)=75.5
      A(15,4)=76.0
      A(16,4)=75.5
      A(17,4)=75.0
      A(18,4)=75.0
```

```
      A(19,4)=74.5
      A(20,4)=75.0
      A(21,4)=71.5
C
C     ----------------------------------------------------------------
C     THE NEXT 21 NUMBERS ARE THE CORRECTION FACTORS
C     USED TO CONVERT TO DBA
C     ----------------------------------------------------------------
C
      C(1)=-19.1
      C(2)=-16.1
      C(3)=-13.2
      C(4)=-10.8
      C(5)=-8.6
      C(6)=-6.5
      C(7)=-4.8
      C(8)=-3.3
      C(9)=-1.9
      C(10)=-0.8
      C(11)=0.0
      C(12)=0.5
      C(13)=1.0
      C(14)=1.2
      C(15)=1.2
      C(16)=1.2
      C(17)=1.0
      C(18)=0.5
      C(19)=-0.2
      C(20)=-1.1
      C(21)=-2.4
C
C     ----------------------------------------------------------------
C     READ IN (N) AND (M) WHERE (N) IS THE NUMBER OF
C     MEASURMENTS OF THE UNKNOWN SOURCE TO BE AVERAGED AND
C     (M) IS THE NUMBER OF MEASURMENTS OF THE REFERENCE
C     SOURCE TO BE AVERAGED
C     ----------------------------------------------------------------
C
C
      READ(5,10)N,M
C
C     ----------------------------------------------------------------
C     READ THE VALUES FOR THE FLUID POWER SYSTEM PARAMETERS
C     NI=OSU PUMP NUMBER, MPR=SYSTEM PRESSURE, MI=INLET
C     PRESSURE, MS= SYSTEM RPM, FR=FLOW RATE, TEM= SYSTEM
C     TEMPERATURE
C     ----------------------------------------------------------------
C
      READ(5,25)NP,MPR,MI,MS,FR,TEM
   25 FORMAT(4I5,2F5.1)
   26 FORMAT(25X,29HSYSTEM PARAMETERS FOR OSU-NP-,I2)
   10 FORMAT(2I5)
C
C     ----------------------------------------------------------------
C     READ THE VALUES FOR THE UNKNOWN SOURCE (LUB)
C     ----------------------------------------------------------------
C
      READ(5,20)((LUB(I,J),I=1,21),J=1,N)
   20 FORMAT(7F10.3)
      IF(N.EQ.1)GO TO 21
C
C     ----------------------------------------------------------------
C     COMPUTE THE AVERAGE OF (N) MEASURMENTS OF (LUB)
C     ----------------------------------------------------------------
C
      DO 40 I=1,21
```

```
      AV=0.0
      DO 30 J=1,M
      AV=AV+LRB(I,J)
   30 CONTINUE
      A(I,2)=AV/M
   40 CONTINUE
      GO TO 55
   21 DO 22 I=1,21
      A(I,2)=LRB(I,1)
   22 CONTINUE
C
C     -----------------------------------------------------------
C     READ THE VALUES FOR THE REFERENCE SOURCE (LRB)
C     -----------------------------------------------------------
C
   55 READ(5,20)((LRB(I,J),I=1,21),J=1,M)
C
C     -----------------------------------------------------------
C     READ THE VALUES FOR THE OUTSIDE SOUND LEVEL (T1)
C     -----------------------------------------------------------
      READ(5,20)(T1(I),I=1,21)
      IF(M.EQ.1)GO TO 23
C
C     -----------------------------------------------------------
C     COMPUTE THE AVERAGE OF (M) MEASURMENTS OF (LRB)
C     -----------------------------------------------------------
C
      DO 70 I=1,21
      AB=0.0
      DO 60 J=1,M
      AB=AB+LRB(I,J)
   60 CONTINUE
      A(I,3)=AB/M
   70 CONTINUE
      GO TO 75
   23 DO 24 I=1,21
      A(I,3)=LRB(I,1)
   24 CONTINUE
C
C     -----------------------------------------------------------
C     READ THE TRANSMISSON LOSS FOR THE ROOM WALL (TO)
C     -----------------------------------------------------------
C
   75 READ(5,20)(TO(I),I=1,21)
C
C     -----------------------------------------------------------
C     READ THE VANE BACKGROUND (VO)
C     -----------------------------------------------------------
C
      READ(5,20)(VO(I),I=1,21)
C
C     -----------------------------------------------------------
C     READ THE BUILDING BACKGROUND (BO)
C     -----------------------------------------------------------
C
      READ(5,20)(BO(I),I=1,21)
C
C     -----------------------------------------------------------
C     READ THE REFERENCE SOURCE FOR CORRECTING (VO) AND (BO)
C     -----------------------------------------------------------
C
      READ(5,20)(LO(I),I=1,21)
C
C     -----------------------------------------------------------
C     READ THE DRIVE BACKGROUND IN THE ROOM (D2)
```

```
C      ---- ---------------------------------------------------
C
       READ(5,20)(R2(I),I=1,21)
C
C      --------------------------------------------------------
C      READ THE DRIVE BACKGROUND OUTSIDE OF THE ROOM (D1)
C      --------------------------------------------------------
C
       READ(5,20)(D1(I),I=1,21)
C
C      --------------------------------------------------------
C      READ THE BUILDING BACKGROUND OUTSIDE OF THE ROOM (B1)
C      --------------------------------------------------------
C
       READ(5,20)(B1(I),I=1,21)
C
C      --------------------------------------------------------
C      READ THE REFERENCE SOURCE FOR CORRECTING (R2)
C      --------------------------------------------------------
C
       READ(5,20)(R2P(I),I=1,21)
C
C      --------------------------------------------------------
C      COMPUTE THE SOUND POWER OF THE UNKNOWN SOURCE IN DBA
C      --------------------------------------------------------
C
       DO 80 I=1,21
       R2DP(I)=10.**((R2P(I)-74.)/10.)
       BOP(I)=BO(I)+A(I,4)-LO(I)
       BP(I)=10.**((BOP(I)-74.)/10.)
       KP(I)=R2DP(I)-BP(I)
       LP(I)=10.**((LO(I)-74.)/10.)
       CP(I)=LP(I)-BP(I)
       IF(BP(I).GT.LP(I))CP(I)=1.0/10.**3.5
       CO(I)=10.*DLOG10(CP(I))+74.
       DO(I)=VO(I)+A(I,4)-CO(I)
       DP(I)=10.**((DO(I)-74.)/10.)
       R2P(I)=DP(I)
       XP(I)=LP(I)-R2P(I)
       IF(R2P(I).GT.LP(I))XP(I)=1.0/10.**3.5
       YO(I)=10.*DLOG10(XP(I))+74.
       KO(I)=10.*DLOG10(KP(I))+74.
       EO(I)=R2(I)+A(I,4)-KO(I)
       EP(I)=10.**((EO(I)-74.)/10.)
       FP(I)=EP(I)-R2P(I)
       IF(R2P(I).GT.EP(I))FP(I)=1.0/10.**3.5
       D1P(I)=10.**((D1(I)-74.)/10.)
       B1P(I)=10.**((B1(I)-74.)/10.)
       GP(I)=D1P(I)-B1P(I)
       IF(B1P(I).GT.D1P(I))GP(I)=1.0/10.**3.5
       GO(I)=10.*DLOG10(GP(I))+74.
       HO(I)=GO(I)-TO(I)
       HP(I)=10.**((HO(I)-74.)/10.)
       DAP(I)=FP(I)-HP(I)
       IF(HP(I).GT.FP(I))DAP(I)=1.0/10.**3.5
       T1P(I)=10.**((T1(I)-74.)/10.)
       OP(I)=T1P(I)-B1P(I)
       IF(B1P(I).GT.T1P(I))OP(I)=1.0/10.**3.5
       OO(I)=10.*DLOG10(OP(I))+74.
       PO(I)=OO(I)-TO(I)
       PP(I)=10.**((PO(I)-74.)/10.)
       PAP(I)=PP(I)+DAP(I)+R2P(I)
       AP(I)=10.**((A(I,3)-74.)/10.)
       QP(I)=AP(I)-R2P(I)
       IF(R2P(I).GT.AP(I))QP(I)=1.0/10.**3.5
       QO(I)=10.*DLOG10(QP(I))+74.
```

```
      DO(I)=A(I,2)+A(I,4)-CC(I)
      BP(I)=10.**((BO(I)-74.)/10.)
      SP(I)=BP(I)-BAP(I)
      IF(BAP(I).GT.BP(I))SP(I)=1.0/10.**3.5
      A(I,5)=A(I,4)-DD(I)
      SO(I)=10.*DLOG10(SP(I))+74.
      A(I,6)=SO(I)
      BAO(I)=10.*DLOG10(BAP(I))+74.
      A(I,7)=BAO(I)
      P(I)=A(I,6)-7.0
      A(I,10)=A(I,6)+C(I)
      A(I,9)=10.**((A(I,10)-74.)/10.)
      A(I,8)=DO(I)
      A(I,11)=A(I,1)
      SOA(I)=SO(I)+C(I)
      SOP(I)=10.**((SOA(I)-74.)/10.)
   80 CONTINUE
      TP=0.0
      SPT=0.0
      DB=0.0
      DO 90 I=1,21
      SPT=SPT+SP(I)
      DB=DB+A(I,10)
      TP=TP+SOP(I)
   90 CONTINUE
      DBT=10.*DLOG10(SPT)+74.
      DBA1=10.*DLOG10(TP)+74.
      DB7=DBA1-7.0
C
C     ----------------------------------------------------------
C     PRINT THE OUTPUT TABLE FOR THE UNKNOWN SOURCE (LUB)
C     ----------------------------------------------------------
C
      WRITE(6,150)
      WRITE(6,150)
      WRITE(6,160)
      WRITE(6,170)
      WRITE(6,120)
      WRITE(6,130)
      WRITE(6,120)
      WRITE(6,100)((A(I,J),J=1,11),I=1,21)
      WRITE(6,120)
      WRITE(6,135)DBT
      WRITE(6,133)TP
      WRITE(6,140)DBA1
      WRITE(6,136)DB7
      WRITE(6,120)
      WRITE(6,26)NP
      WRITE(6,27)NPR,NS,TEM,FR,NI
      WRITE(6,120)
      WRITE(6,125)
  100 FORMAT(1X,F6.0,7F7.1,1X,F8.4,F7.1,3X,F6.0)
  120 FORMAT(1X,80H-----------------------------------------------------------
     1-------------------------- )
  125 FORMAT(////)
  130 FORMAT(2X,80HFREQ     LUB     LPB     LF     CORR     LU     BA     VA
     1     PWR     DBA     FREQ     )
  133 FORMAT(1X,57HTOTAL "A" WEIGHTED POWER ----------------------------
     1----,F7.4)
  134 FORMAT(9X,63H"ACTUAL LEVELS ARE LESS THAN OR EQUAL TO THOSE PRESEN
     1TED BELOW")
  135 FORMAT(1X,36HUNWEIGHTED SOUND POWER -------------,F6.2,1X,2HDB)
  136 FORMAT(1X,66HTHREE FEET FROM THE SOURCE IN A HEMISPHERICALLY DIVER
     1GENT FIELD***,F6.2,1X,7HDBA ***)
  140 FORMAT(1X,66H"A" WEIGHTED SOUND POWER ----------------------------
     1-------------,F6.2,1X,3HDBA)
```

```
  150 FORMAT(/)
  160 FORMAT(37X,8HOSU-EPRC)
  170 FORMAT(26X,29HACOUSTICS LABORATORY DATA LOG)
   27 FORMAT(1X,9HPRESSURE=,I4,3HPSI,2X,6HSPEED=,I4,3HRPM,2X,12HTEMPERAT
     1URE=,F4.1,1HC,2X,10HFLOW RATE=,F4.1,1HG,2X,6HINLET=,I2,3HPSI)
      STOP
      END
//GO.SYSIN DD *
```

- INPUT DATA -

```
     1    1
    10  200    0 2000 26.8 38.0
57.3    62.7    56.8    59.9    74.2    66.8    61.3
63.9    71.1    71.4    64.8    59.     58.2    56.7
58.6    57.     56.9    57.3    58.3    59.     56.3
68.7    71.7    72.8    75.9    75.7    75.2    74.7
73.3    73.7    74.2    74.2    74.7    75.1    74.9
75.2    74.9    73.6    73.1    73.3    72.9    67.3
61.7    64.5    61.5    70.9    86.     78.8    68.
77.9    74.2    81.8    80.3    78.8    71.     69.8
69.5    66.     68.7    69.8    70.3    69.     64.3
20.     21.5    24.     26.     28.     29.5    32.5
34.5    34.5    34.5    34.5    34.5    34.5    34.5
34.5    34.5    36.     39.     42.     44.5    47.
52.2    56.2    52.     49.     50.     53.9    58.3
57.6    54.5    54.     51.2    50.3    51.     48.2
51.9    49.     46.6    45.     45.2    45.8    41.7
47.2    39.     39.     39.     39.     39.     39.
39.     39.     39.     39.     39.     39.     39.
39.     39.     39.     39.     39.     39.     39.
72.     72.     74.     76.3    77.     77.3    75.7
74.     74.     74.2    74.3    75.     75.     74.9
75.1    74.5    73.1    72.6    72.8    72.4    66.7
60.8    69.     61.1    56.7    61.1    60.6    58.
61.6    59.     63.8    59.     57.6    63.8    54.8
54.8    54.6    48.8    50.2    48.2    45.7    43.5
61.2    66.6    64.2    71.5    75.8    70.     71.3
83.6    76.3    78.2    78.7    76.1    73.2    73.3
72.3    69.     69.6    75.1    75.2    72.9    65.7
48.3    48.6    43.3    43.6    39.     39.     39.
39.     39.     39.     39.     39.     39.     39.
39.     39.     39.     39.     39.     39.     39.
70.9    71.1    73.5    75.6    75.8    76.4    74.9
73.6    74.2    74.6    74.6    75.2    75.3    75.
75.3    75.2    74.     73.8    74.2    73.8    68.3
```

```
//NOISF*** JOB (                         ,1),'NOISE',MSGLEVEL=(0,0),
//    CLASS=B
/*ROUTE PRINT RJO
// EXEC FORTHCL
//FORT.SYSIN DD *
      DIMENSION
```

- MAIN PROGRAM -

```
      END
//LKED.SYSLMOD DD DSNAME=OSU.ACT12687.FPRC,DISP=OLD
//LKED.SYSIN DD *
  NAME DRA(R)
//
```

- CALLING PROGRAM -

```
//DRAXXXXX JOB (                         ,1),'ELLIOTT',MSGLEVEL=(0,0)
/*ROUTE PRINT RJO
// EXEC PGM=DRA
//STEPLIB DD DSNAME=OSU.ACT12687.FPRC,DISP=SHR
//FT05F001 DD *
    1    1
   10  200     0 2000 26.8 38.0
57.3      62.7      56.8      59.9      74.2      66.8      61.3
63.9      71.1      71.4      64.8      59.       58.2      56.7
58.6      57.       56.9      57.3      58.3      59.       56.3
68.7      71.7      72.8      75.9      75.7      75.7      74.7
73.3      73.7      74.2      74.2      74.7      75.1      74.9
75.2      74.9      73.6      73.1      73.3      72.9      67.3
61.7      64.5      61.5      70.9      86.       78.8      68.
77.9      74.2      81.8      80.3      78.8      71.       69.8
69.5      66.       68.7      69.8      70.3      69.       64.3
20.       21.5      24.       26.       28.       29.5      32.5
34.5      34.5      34.5      34.5      34.5      34.5      34.5
34.5      34.5      36.       39.       42.       44.5      47.
52.2      56.2      52.       49.       50.       53.9      58.3
57.6      54.5      54.       51.2      50.3      51.       48.2
51.9      49.       46.6      45.       45.2      45.8      41.7
47.2      39.       39.       39.       39.       39.       39.
39.       39.       39.       39.       39.       39.       39.
39.       39.       39.       39.       39.       39.       39.
72.       72.       74.       76.3      77.       77.3      75.7
74.       74.       74.2      74.3      75.       75.       74.9
75.1      74.5      73.1      72.6      72.8      72.4      66.7
60.8      69.       61.1      56.7      61.1      60.6      58.
61.6      59.       63.8      59.       57.6      63.8      54.8
54.8      54.6      48.8      50.2      48.2      45.7      43.5
61.2      66.6      64.2      71.5      75.8      70.       71.3
83.6      76.3      78.2      78.7      76.1      73.2      73.3
72.3      69.       69.6      75.1      75.2      72.9      65.7
48.3      48.6      43.3      43.6      39.       39.       39.
39.       39.       39.       39.       39.       39.       39.
39.       39.       39.       39.       39.       39.       39.
70.9      71.1      73.5      75.6      75.8      76.4      74.9
73.6      74.2      74.6      74.6      75.2      75.3      75.
75.3      75.2      74.       73.8      74.2      73.8      68.3
//FT06F001 DD SYSOUT=A
//
```

APPENDIX C

INSTRUMENTATION

INSTRUMENTATION

I. GENERAL RADIO

A.	1521-A	Strip Chart Recorder
B.	1523	Level Recorder
C.	1523-P1	Preamplifier Plug In
D.	1523-P3	1/3 Octave Band Analyzer
E.	1523-9621	25dB Potentiometer
	1523-9622	50dB Potentiometer
	1523-9624	100dB Potentiometer
F.	1560-9531	Microphone
G.	1560-9580	Tripod
H.	1560-9666	Microphone Cable
I.	1560-P13	Vibration Pickup System
J.	1560-P42	Microphone Preamplifier
K.	1562-A	Sound Level Calibrator
L.	1382	Random Noise Generator

II. HEWLETT PACKARD

A.	3300-A	Function Generator

III. BRUEL + KJAER

A.	2107	Frequency Analyzer

IV. BOGEN

A.	CH13-35A	Amplifier

V. TEKTRONIX

A.	502	Dual-Beam Oscilloscope

VI. PCB PIEZOTRONICS, INC.

A.	118A02	Quartz Crystal Pressure Transducer
B.	402A	Pressure Amplifier

C. 482-A . . . . ICP Power Supply

VII. BELL + HOWELL

A. 4-402-0001 . . . . Pressure Transducer

VIII. DAYTRONIC

A. Type 91 . . . . Strain Gage Transducer Input Module

B. Model 300 . . . . Transducer Amplifier-Indicator

C. Type P . . . . Galvanometer Driver Output Module

APPENDIX D

ELECTRONIC ACOUSTICAL TEST FACILITY REFERENCE SOURCE

A schematic and listing of the components used in the construction of the electronic reference source discussed in Chapter IV are presented in this appendix. The source's electronic stability is estimated to be approximately 1.12%. Its primary function is the production of ultra-stable sound levels in three different modes of operation. The various outputs are:

1. Broad-Band Noise
2. 500 Hz. Pure Tone
3. 500 Hz. Center Frequency Pure Tone Which Oscillates $\pm$ 10% in Frequency Over a 10 Second Period

All three modes will be used during the proposed survey of the fluid power industry's acoustical test facilities.

LIST OF ELECTRONIC COMPONENTS

Component	Manufacturer	Model Number
Power Supply	ACDC Electronics, Inc.	OA15D1.1-1
Power Supply	Elgenco	3609-A
White Noise Generator	Elgenco	3606A55124
Low Frequency Oscillator	W. H. Ferwalt, Inc.	SP01088
Voltage Controlled Oscillator	W. H. Ferwalt, Inc.	VC068513
Operational Amplifiers	Analog Devices	144A
Audio Amplifier	Arvee Engineering	202
Speaker	Altec Lansing	755-E

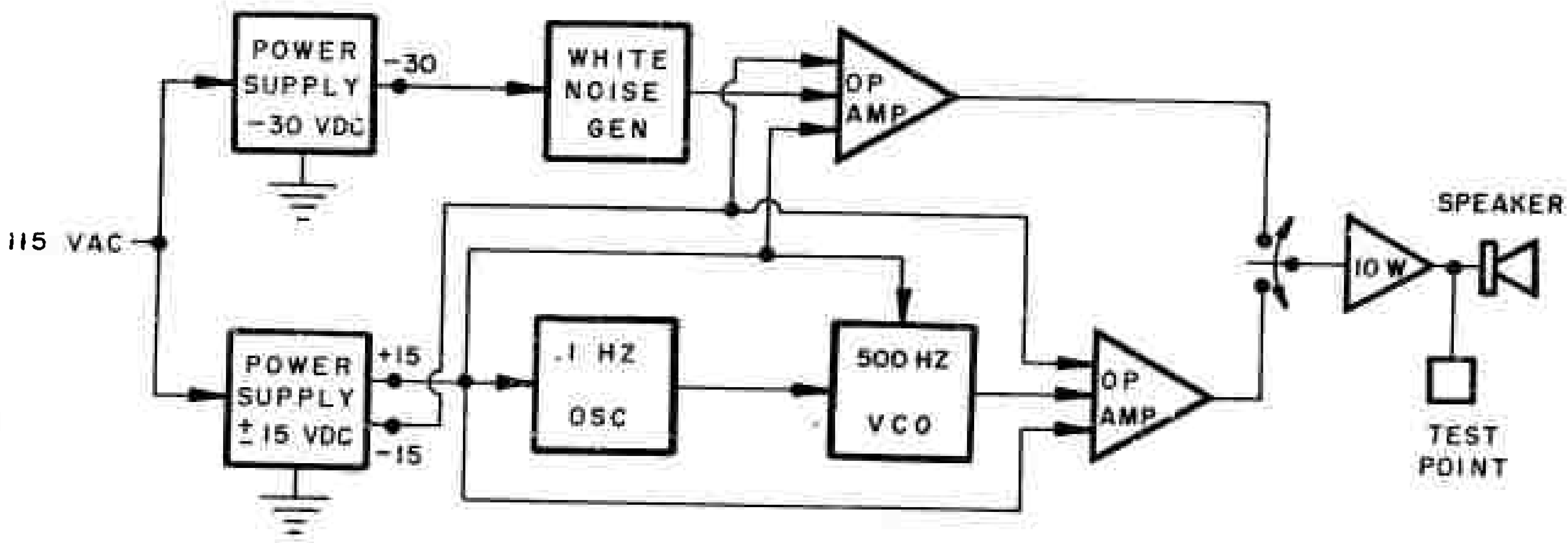

Fig. D-1. Schematic of Electronic Noise Box (ENB).

APPENDIX E

COMPUTER PROGRAM FOR FLUIDBORNE NOISE REDUCTION

This appendix provides a listing of the computer program discussed in Chapter VII. The program inputs are (PUB), the fluidborne noise level, and (PRB), the background noise in the system. Both (PUB) and (PRB) are pressure levels in the 1/3 octave bands between 100 Hz. and 10,000 Hz. The program corrects (PUB) to account for the background noise (PRB). The output includes the total pressure, dBA weighted pressure, and dBA weighted pressure relative to 20 micro-neutrons per meter squared.

```
//PSI***** JOB (      ,           ,1),'ELLIOTT',MSGLEVEL=(0,0)
/*ROUTE PRINT RJO
// EXEC FORTGCG
//FORT.SYSIN DD *
      DIMENSION A(21,9),PUB(21,10),PRB(21,10),C(21),P(21),
     1AP2(21),AP3(21),CP(21),UP(21)
      DOUBLE PRECISION A,PUB,PRB,C,P,AP2,AP3,CP,DB,UP,TP,DB1,DBA
C
C     ----------------------------------------------------
C     THE FOLLOWING 21 NUMBERS ARE THE 1/3 OCTAVE CENTER
C     FREQUENCIES THAT ARE USED IN THIS PROGRAM
C     ----------------------------------------------------
C
      A(1,1)=100
      A(2,1)=125
      A(3,1)=160
      A(4,1)=200
      A(5,1)=250
      A(6,1)=315
      A(7,1)=400
      A(8,1)=500
      A(9,1)=630
      A(10,1)=800
      A(11,1)=1000
      A(12,1)=1250
      A(13,1)=1600
      A(14,1)=2000
      A(15,1)=2500
      A(16,1)=3150
      A(17,1)=4000
      A(18,1)=5000
      A(19,1)=6300
      A(20,1)=8000
      A(21,1)=10000
C
C     ----------------------------------------------------
C     THE NEXT 21 NUMBERS ARE THE CORRECTION FACTORS
C     USED TO CONVERT TO DBA
C     ----------------------------------------------------
C
      C(1)=-19.1
      C(2)=-16.1
      C(3)=-13.2
      C(4)=-10.8
      C(5)=-8.6
      C(6)=-6.5
      C(7)=-4.8
      C(8)=-3.3
      C(9)=-1.9
      C(10)=-0.8
      C(11)=0.0
      C(12)=0.5
      C(13)=1.0
      C(14)=1.2
      C(15)=1.2
      C(16)=1.2
      C(17)=1.0
      C(18)=0.5
      C(19)=-0.2
      C(20)=-1.1
      C(21)=-2.4
C
C     ----------------------------------------------------
C     READ IN THE NUMBER OF MEASURMENTS TO BE AVERAGED--( N
C     MEASURMENTS FOR THE PRESSURE SOURCE, M FOR THE
C     BACKGROUND NOISE, FORMAT(2I5)
```

```
C     ------------------------------------------------------
C
      READ(5,10)N,M
   10 FORMAT(2I5)
      READ(5,11)TX
   11 FORMAT(F10.2)
      READ(5,12)NO
      READ(5,12)OP
      READ(5,12)IP
      READ(5,12)IS
      READ(5,11)FR
      READ(5,11)TE
   12 FORMAT(I5)
C
C     ------------------------------------------------------
C     READ IN THE MEASURED VALUES FOR THE PRESSURE SOURCE
C     FORMAT(7F10.0)
C     ------------------------------------------------------
C
      READ(5,20)((PUB(I,J),I=1,21),J=1,N)
   20 FORMAT(7F10.0)
C
C     ------------------------------------------------------
C     FIND THE AVERAGE OF N MEASURMENTS FOR EACH 1/3 OCTAVE
C     BAND FOR THE PRESSURE SOURCE
C     ------------------------------------------------------
C
      DO 40 I=1,21
      AV=0.0
      DO 30 J=1,N
      AV=AV+PUB(I,J)
   30 CONTINUE
      A(I,2)=AV/N
   40 CONTINUE
C
C     ------------------------------------------------------
C     READ IN THE MEASURED VALUES FOR THE BACKGROUND,
C     FORMAT(7F10.0)
C     ------------------------------------------------------
C
      READ(5,20)((PRB(I,J),I=1,21),J=1,M)
C
C     ------------------------------------------------------
C     FIND THE AVERAGE OF M MEASURMENTS FOR EACH 1/3 OCTAVE
C     BAND FOR THE BACKGROUND
C     ------------------------------------------------------
C
      DO 70 I=1,21
      AB=0.0
      DO 60 J=1,M
      AB=AB+PRB(I,J)
   60 CONTINUE
      A(I,3)=AB/M
   70 CONTINUE
      DO 80 I=1,21
C
C     ------------------------------------------------------
C     CORRECT THE PRESSURE SOURCE WITH THE BACKGROUND
C     ------------------------------------------------------
      AP2(I)=10.**((A(I,2)-74.)/10.)
      AP3(I)=10.**((A(I,3)-74.)/10.)
      CP(I)=AP2(I)-AP3(I)
      IF(AP3(I).GE.AP2(I))CP(I)=1/10.**3.5
C
C     ------------------------------------------------------
C     COMPUTE THE CORRECTED PRESSURE LEVELS
```

```
C     --------------------------------------------------------
C
      A(I,4)=10.*DLOG10(CP(I))+74.
C
C     --------------------------------------------------------
C     COMPUTE THE "A" WEIGHTED PRESSURE LEVELS
C     --------------------------------------------------------
C
      A(I,5)=A(I,4)+C(I)
C
C     --------------------------------------------------------
C     COMPUTE THE POWER ASSOCIATED WITH THE "A" WEIGHTED
C     PRESSURE LEVELS
C     --------------------------------------------------------
C
      A(I,6)=10.**((A(I,5)-74.)/10.)
C
C     --------------------------------------------------------
C     COMPUTE THE POWER ASSOCIATED WITH THE UNWEIGHTED
C     PRESSURE LEVELS
C     --------------------------------------------------------
C
      UP(I)=10.**((A(I,4)-74.)/10.)
C
C     --------------------------------------------------------
C     COMPUTE THE "A" WEIGHTED PRESSURE LEVELS RELATIVE TO
C     20 MN/M**2
C     --------------------------------------------------------
C
      A(I,7)=A(I,5)+TX
      A(I,8)=A(I,1)
   80 CONTINUE
      TP=0.0
      DB=0.0
      DO 90 I=1,21
      DB=DB+A(I,6)
      TP=TP+CP(I)
   90 CONTINUE
C
C     --------------------------------------------------------
C     COMPUTE THE TOTAL UNWEIGHTED PRESSURE LEVEL
C     --------------------------------------------------------
C
      DB1=10.*DLOG10(TP)+74.
C
C     --------------------------------------------------------
C     COMPUTE THE TOTAL "A" WEIGHTED PRESSURE LEVEL
C     --------------------------------------------------------
C
      DBA=10.*DLOG10(DB)+74.
C
C     --------------------------------------------------------
C     COMPUTE THE TOTAL "A" WEIGHTED PRESSURE LEVEL RELATIVE
C     TO 20 MN/M**2
C     --------------------------------------------------------
      DBA2=DBA+TX
C
C     --------------------------------------------------------
C     PRINT THE OUTPUT TABLE
C     ----------------------------------------
      WRITE(6,169)
      WRITE(6,120)
      WRITE(6,130)
      WRITE(6,150)
      WRITE(6,140)
```

```
      WRITE(6,150)
      WRITE(6,100)((A(I,J),J=1,8),I=1,21)
      WRITE(6,150)
      WRITE(6,101)DB1
      WRITE(6,102)DBA
C
      WRITE(6,103)DB
      WRITE(6,104)DBA2
      WRITE(6,150)
      WRITE(6,170)NO
      WRITE(6,175)OP,IP,IS,FR,TE
      WRITE(6,150)
      WRITE(6,169)
  100 FORMAT(1X,F6.0,4F10.2,5X,F6.4,1X,F10.2,F11.0)
  101 FORMAT(1X,30HTOTAL PRESSURE ---------------,F6.2,1X,2HDB)
  102 FORMAT(1X,40H"A" WEIGHTED PRESSURE ------------------,F6.2,4H DBA)
  103 FORMAT(1X,50HTOTAL "A" WEIGHTED POWER -------------------------,
     1F7.4)
  104 FORMAT(1X,61H"A" WEIGHTED PRESSURE RELATIVE TO 20 MN/M**2 --------
     1--------,F7.2,4H DBA)
  110 FORMAT(4F10.3)
  120 FORMAT(36X,8HOSU-FPRC)
  130 FORMAT(26X,29HACOUSTICS LABORATORY DATA LOG)
  140 FORMAT(2X,4HFREQ,6X,5HPRESS,6X,3HBKG,6X,4HCORR,7X,3H"A",6X,
     15HPOWER,6X,6HREL-20,6X,4HFREQ)
  150 FORMAT(80H ********************************************************
     1************************)
  169 FORMAT(////)
  170 FORMAT(25X,29HSYSTEM PARAMETERS FOR OSU-NP-,I2)
  175 FORMAT(1X,9HPRESSURE=,I4,3HPSI,2X,6HINLET=,I1,3HPSI,2X,
     16HSPEED=,I4,3HRPM,2X,10HFLOW RATE=,F4.1,1HG,2X,
     212HTEMPERATURE=,F4.1,1HC)
      STOP
      END
//GO.SYSIN DD *
    1     1
  124.
    0
 2000
    0
 2000
   0.0
  65.5
52.         57.5       52.2       59.1       74.3       72.5       60.9
57.8        73.7       64.3       62.2       62.9       63.        60.9
58.8        60.1       54.2       43.5       42.5       42.3       43.9
46.5        46.2       51.5       52.5       45.        49.6       39.
39.         39.        39.        39.        39.        39.        39.
39.         39.        39.        39.        39.        39.        39.
//
```

APPENDIX F

ISOLATION MATERIALS

The following materials are being used to acoustically treat fluid lines, pump mounts, pump drive systems, and the drive support system:

1. "Duct Board" -- Rigid fiberglass with aluminum back. Owens-Corning Type 475-FR(SD)

2. Leaded Vinyl -- John Schneller & Associates, Sound/Eaze TLB-M, TLB-L

3. Leaded Vinyl -- Singer Partitions, Inc.; Super Sound Stopper

4. Aluminum Foil Reinforced Insulation -- Supplier, L. A. King Co.; Type MRA; 0.6 lb/ft^3, 1 in. insulation with foil scrim kraft, light duty, NFBU rated, manufactured by Certainteed - St. Gobain

5. Foamrubber -- 2 inch thick, 21 oz/ft.^{3}, (21,000 gm/m^3)

APPENDIX G

TEST CODE FOR MEASURING AND REPORTING AIRBORNE NOISE

EMITTED BY HYDRAULIC FLUID POWER PUMPS

NOTE: This document was developed with the guidance of the fluid power industry and a Tri-Level Conference on noise attended by representatives from the NFPA, ANSI, and USTAG.

REFERENCES*

1. American National Standard Glossary of Terms for Fluid Power, ANSI/ B93.2, and Supplements Thereto. (ISO/TC 131/SC 1 USA- ___).

2. ISO Recommendation R495, General Requirements for the Preparation of Test Codes for Measuring the Noise Emitted by Machines.

3. ISO Recommendation R1000, International Standard Rules for the Use of Units of the International System of Units and a Selection of the Decimal Multiples and Sub-Multiples of SI Units.

4. ISO Recommendation R1680 Part II), Test Code for the Measurement of the Airborne Noise Emitted by Rotating Electrical Machinery.

5. ISO Recommendation 2204, Guide to the Measurement of Acoustical Noise and Evaluation of Its Effects on Man.

6. American Standard Recommended Practice Z24.19-1957.

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*Unless otherwise noted, all references shall be in accordance with the latest revision.

CONTENTS

TABLES

TEST CODE FOR MEASURING AND REPORTING AIRBORNE NOISE EMITTED BY HYDRAULIC FLUID POWER PUMPS

INTRODUCTION

In hydraulic fluid power systems, power is transmitted and controlled through a liquid under pressure within an enclosed circuit. Pumps convert mechanical power into hydraulic fluid power. Some noise is created during the power conversion process. The sound level which results because of noise emitted by the pump is an important consideration in component selection. The results of this procedure are intended for comparing the sound levels of different pumps.

1. SCOPE

To include the measurement and reporting of the airborne noise emitted by any hydraulic fluid power pump:

1.1 In terms of A-weighted sound power level.

1.2 In terms of octave-band, sound-power levels.

1.3 Excludes the determination of directivity characteristics of the acoustic radiations.

1.4 Does not exclude the measurement of fluid or structure-borne forms of sound inducing energy when standards for such measurements are promulgated.

2. PURPOSE

To establish a uniform basis for measuring, reporting, and accurately comparing the sound levels of hydraulic fluid power pumps.

3. TERMS AND DEFINITIONS

4. UNITS

4.1 The International System of Units (SI) is used in accordance with Ref. No. 3.

4.2 Approximate conversions to "customary US" units are given

for informational purposes. These appear in parenthesis after their SI counterpart.

5. LETTER SYMBOLS

The following letter symbols are used in this document:

(This portion to be completed later.)

6. OUTLINE OF PROCEDURES

6.1 Set up and maintain apparatus per Sections 7, 8, and 9.

6.2 Run all tests per Section 10.

6.3 Present data from Section 10 per Section 11.

7. GENERAL

Tests are to be made in rooms providing a free-field over a reflecting plane, reverberant field, or a semi-reverberant field, in conformance with Part II, Ref. 4, except for the following exceptions.

NOTE: FUTURE ISO RECOMMENDATIONS THAT SUPERSEDE REF. 4 ARE TO BE USED AS THEY BECOME AVAILABLE.

7.1 When measurements are made under free field over a reflecting surface or semi-reverberant conditions, the microphone positions shall be arranged over a hemispherical surface centered about the center of the projection of the pump on the reflecting plane.

7.1.1 The radius of the hemispherical surface shall be more than twice the maximum dimension of the pump (ignoring minor projections such as the shaft) but no less than one meter.

7.1.2 Use at least 4 positions located central to equal areas of the hemispherical surface (See Table 1).

TABLE 1: COORDINATES FOR 4-POINT MICROPHONE ARRAY

$\frac{X}{r}$	$\frac{Y}{r}$	$\frac{Z}{r}$
.40	.73	.53
.40	-.73	.53
.84	0	.53
0	0	1

Shaft at -x,y=0: Z is vertical.

7.1.3 Sound power level shall be computed from the following equation:

$$L_{pa} \text{ (or } L_p) = L_{p(m)} + 20 \log_{10} r + 8 + K_1$$

where: r is the radius (meters) of the semihemispher and other terms as given in Ref. 4. For K_1, see paragraph 13.1.9 of Ref. 4.

7.2 Measurements may be made under reverberant conditions, although the pump noise spectra contain discrete frequencies, when moving vanes or a traversing microphone are used to provide additional diffusion or an array of at least 3 microphones is used to provide a space average. A single microphone position can be used if adequate diffusion has been shown to exist in accordance with paragraph 13.2.2 of Ref. 4.

8. TEST EQUIPMENT

8.1 Hydraulic Equipment.

8.1.1 Use a fluid conditioning circuit to provide specified conditions, temperature, filtration, and aeration.

8.1.2 Use a control filter which will limit the total number of particles in the system to 1500 particles per milliliter greater than 10 micrometers.

8.1.3 Use a test fluid as specified by the test requirements.

8.1.4 Use the largest practical line size.

8.1.5 Exercise extra care in assembling inlet lines to prevent air leaking into the circuit.

8.1.6 Locate inlet restrictor valves upstream of the pump as far as practical to minimize out-gassing due to turbulence.

8.1.7 Wrap all fluid lines and load valves in the test space with acoustical barrier material as desired. A suitable material will have at least a 10dB transmission loss at 100 Hz. and higher frequencies. See Ref. 6.

8.1.8 Locate the inlet pressure gage at the same height as the inlet fitting or calibrate gage for height difference.

8.2 Mechanical Equipment.

8.2.1 Either locate the drive motor outside the test space and drive the pump through a long shaft or isolate the motor in an enclosure.

8.2.2 Construct the pump mount so that it will not add to or detract from the pump noise.

8.3 Test Space.

8.3.1 Verify the suitability of the test space per the appropriate procedure in Ref. 4.

8.4 Acoustical Instruments.

8.4.1 Secure instrumentation that complies with the measuring instrument requirements of Ref. 4.

8.4.2 Calibrate the measuring instruments per Ref. 4.

9. TEST CONDITIONS ACCURACY

Set up and maintain equipment accuracy within the limits in Table 2.

10. TEST PROCEDURE

10.1 Background Measurements.

10.1.1 Disconnect the drive shaft coupling at the pump.

10.1.2 Operate the pump drive system at the speed specified in the test requirements.

10.1.3 Obtain the background mean levels at each octave band center frequency between 125 Hz. and 8000 Hz. per Ref. 4.

10.1.4 Record the results of Clause 10.1.3 (See Table 3).

NOTE: IT IS RECOMMENDED THAT THE BACKGROUND LEVELS BE OBTAINED WHILE THE SYSTEM IS OPERATING UNDER TEST CONDITIONS WITH THE PUMP COVERED BY A SOUND ISOLATOR WITH A NOTICEABLE TRANSMISSION LOSS. IF, AFTER PROPERLY COVERING THE PUMP, THE SOUND LEVEL DOES NOT NOTICEABLY DECREASE, THEN IT IS HIGHLY PROBABLE THAT THE MEASURED LEVEL IS NOT ASSOCIATED WITH THE PUMP AND THE TEST SHOULD BE REJECTED.

TABLE 2: TEST CONDITIONS ACCURACY

Test Condition	SI Unit	US Unit	Maintain Within ±
Flow	liters/min.	USGPM	2%
Pressure, Pump Inlet	(Positive) bar (Negative) mmHg	psig m Hg	2%
Pressure	bar	psig	2%
Speed	RPM	RPM	2%
Temperature	°C	°F	3°C (5°F)

10.2 Pump Measurements.

10.2.1 Connect the pump drive shaft coupling.

10.2.2 Measure temperatures and pressures at the pump inlet and discharge fittings or test station provided by the manufacturer.

10.2.3 Operate the pump at conditions specified in the test requirement.

10.2.4 Insure that the pump has been "broken-in" per manufacturer's recommended procedure or operate for a minimum of one hour at specified conditions.

10.2.5 The test circuit should be operated for sufficient time to establish a stabilized condition of all variables including fluid condition. Maintain conditions within specified limits in Table 2.

10.2.6 Obtain measured pump mean levels at each octave band center frequency between 125 Hz. and 8000 Hz. per Ref. 4.

10.2.7 Record the results of Clause 10.2.6 (See Table 3).

10.3 Corrected Pump Measurements.

TABLE 3

Example Data Summary

Pump Description ____________ Fluid ____________

____________ Temp. (Inlet) ______ (°C/°F)

Test Location ____________ Viscosity ______ (cSt, SUS)

Test Date ____________ Shaft Speed ______ RPM

Discharge Pressure ______ (bar/psig) Output Flow ______ (l/min;USGPM)

Inlet Pressure ______ (mm/in Hg) (bar/psig) % Displacement ______ %

Case Pressure ______ (mm/in Hg) (bar/psig) Compensatur Setting ______

Type of Test Space ____________ Date Test Space Verified ______

Results of Test Space Verification ____________

____

Measured Background Mean Pressure Level (dB)							
Measured Pump Mean Pressure Level (dB)							
Correction To Pump Measurements (dB)							
Pump Mean Pressure Level (dB)							
Octave Band Centered On (Hz)	125	250	500	1000	2000	4000	8000

Sound Power Level ______ dBA

10.3.1 Correct the pump measurements of Clause 10 relative to the background results of Clause 10.1 per Ref. 4 and Clause 10.3.2 (See Table 3).

10.3.2 Void the test if the difference between pump and background levels of Clause 10.3.1 is less than 6 dBA sound pressure. Exception: A manufacturer can use such data with a maximum of 1dB background correction where the error prejudicial to his product is deemed acceptable.

10.3.3 Record the results of Clause 10.3.1 (See Table 3).

10.4 (A) Weighted Sound Power Level.

10.4.1 Calculate per Ref. 4, the (A) weighted sound power level using the results of Clause 10.3.

10.4.2 Record the results of Clause 10.4.1 (See Table 3).

11. <u>DATA PRESENTATION</u>

11.1 Prepare a data summary using the results of Section 9.

11.2 Use Table 3 as an example summary.

11.3 Include the following information on the summary.

11.3.1 Pump description.

11.3.2 Fluid viscosity (cSt, SUS).

11.3.3 Date of test.

11.3.4 Location of test.

11.3.5 Shaft speed.

11.3.6 Discharge pressure.

11.3.7 Inlet pressure.

11.3.8 Inlet temperature.

11.3.9 Type of fluid.

11.3.10 Output flow for variable displacement units also state percentage displacements, i.e. 90%, 5%, etc.

11.3.11 Case pressure.

11.3.12 Compensator setting.

11.3.13 Type of test space.

11.3.14 Results of test space verification.

12. JUSTIFICATION STATEMENT

(To be includea following the review process.)

APPENDIX H

TEST CODE FOR MEASURING AND REPORTING FLUIDBORNE NOISE

EMITTED BY HYDRAULIC FLUID POWER PUMPS

NOTE: This document is not considered complete, but it is intended to serve as a guide for the development of a test method for fluidborne noise.

REFERENCES*

1. American National Standard Glossary of Terms for Fluid Power, ANSI/B93.2, and Supplements Thereto. (ISO/TC 131/SC 1 USA-___).

2. ISO Recommendation R495, General Requirements for the Preparation of Test Codes for Measuring the Noise Emitted by Machines.

3. ISO Recommendation R1000, International Standard Rules for the Use of Units of the International System of Units and a Selection of the Decimal Multiples and Sub-Multiples of SI Units.

4. ISO Recommendation R1680, Test Code for the Measurement of the Airborne Noise Emitted by Rotating Electrical Machinery.

5. Society of Automotive Engineers Aerospace Recommended Practice, Determination of Hydraulic Pressure Drop, SAE/ARP 24B-1968.

*Unless otherwise noted, all references shall be in accordance with the latest revision.

CONTENTS

TABLES

TEST CODE FOR MEASURING AND REPORTING FLUIDBORNE NOISE EMITTED BY HYDRAULIC FLUID POWER PUMPS

INTRODUCTION

In hydraulic fluid power systems, power is transmitted and controlled through a liquid under pressure within an enclosed circuit. Pumps convert mechanical power into hydraulic fluid power. Pressure pulsations are created in the hydraulic fluid during the power conversion process. These pressure pulsations transmit vibrational energy to fluid conduits and other components. The transmitted pulsations may ultimately cause airborne noise. A pump's potential for directly causing airborne noise is an important consideration in component selection. The results of this procedure might be used to compare the pressure pulsations caused by two different pumps.

1. SCOPE

To include the measurement and reporting of the pressure pulsations caused by any hydraulic fluid power pump.

2. PURPOSE

To provide a means of comparing pressure pulsations associated with hydraulic fluid power pumps where the comparable data has been measured and reported according to a specific test procedure.

3. TERMS AND DEFINITIONS

4. UNITS

4.1 The International System of Units (SI) is used in accordance with Ref. No. 3.

4.2 Approximate conversions to "Customary U.S." units are given for informational purposes. These appear in parenthesis after their SI counterpart.

5. LETTER SYMBOLS

(This portion to be completed later.)

6. GENERAL

6.1 Set up and maintain apparatus per Sections 7 and 8.

6.2 Run all tests per Section 9.

6.3 Present data from Section 9 per Section 10.

7. TEST EQUIPMENT

7.1 Hydraulic Equipment.

7.1.1 Use a fluid conditioning circuit as required.

7.1.2 Use a control filter which will limit the total number of particles in the system to 1500 particles per milliliter greater than 10 micrometers.

7.1.3 Use a test fluid as specified by the test requirements.

7.1.4 Exercise extra care in assembling inlet lines to prevent air leaking into the circuit.

7.1.5 Locate inlet restrictor valves upstream of the pump as far as practical to minimize out-gassing due to turbulence.

7.1.6 Locate the inlet pressure gage at the same height as the inlet fitting or calibrate gage for height difference.

7.1.7 Use a needle valve (load valve) to creat the required pump outlet pressure.

7.1.8 Locate the load valve at least 25 feet downstream of the pump outlet.

7.1.9 Locate a piezometer tube, constructed per Ref. 5 and of the same tube size as the pump outlet, as close as practical to the pump outlet.

7.1.10 Install a pressure pulsation attenuator, which dampens 20dB at 100 Hz. and higher frequencies, downstream of the piezometer tube.

7.2 Mechanical Equipment.

7.2.1 Construct the pump mount so that it will not add to or detract from the pressure pulsations.

7.3 Test Circuit.

7.3.1 Verify the suitability of the test circuit per the appropriate procedure.

7.4 Measuring Instruments.

7.4.1 Acoustical Analysis Instruments.

7.4.1.1 Secure instrumentation that complies with the measuring instrument requirements of Ref. 4.

7.4.1.2 Calibrate the measuring instruments per Ref. 4.

7.4.2 Measure temperatures and pressures at the pump inlet and discharge fittings.

7.4.3 Pressure Instrumentation.

7.4.3.1 Secure a dynamic pressure transducer and associated conditioning equipment which has an output voltage linearally proportional to pressure within $\pm$ 4% over a frequency range of 100 Hz. to 10,000 Hz. and a time constant of less than 15 seconds.

7.4.3.2 Insure that each unit in the pressure instrumentation system is calibrated at least every six months.

8. TEST CONDITIONS ACCURACY

Set up and maintain equipment accuracy within the limits of Table 1.

Table 1: Test Conditions Accuracy.

Test Conditions	SI Unit	U.S. Unit	Maintain Within $\pm$
Flow	liters/min.	U.S. GPM	2%
Pressure, Pump	(Positive) bar	psig	2%
Inlet	(Negative)mm Hg	in Hg	2%
Pressure	bar	psig	2%
Speed	RPM	RPM	2%
Temperature	°C	°F	3°C (5°F)

9. TEST PROCEDURE

9.1 Transducer Preparations.

9.1.1 Attach pressure transducer to piezometer tube with a minimum of tubing.

9.1.2 Insure that no air is trapped in the connecting line between the transducer and the piezometer tube.

9.2 Pulsation Measurements.

9.2.1 Operate the pump at conditions specified in the test requirement.

9.2.2 Insure that the pump has been operated at test conditions for one hour previously or operate at specified conditions for one hour.

9.2.3 Stabilize all test conditions.

9.2.4 Wait 60 seconds after reaching a stabilized operating condition before proceeding to Clause 9.2.5.

9.2.5 Obtain measured pulsation mean levels in dB at each octave band center frequency between 125 Hz. and 8000 Hz.

9.2.6 Convert measurements of Clause 9.2.6 to dB values relative to $20\mu\ N/M^2$.

9.2.7 Record the results of Clause 9.2.6 (See Table 2).

9.3 (A) Weighted Pressure Power Level.

9.3.1 Calculate 1, per Ref. 4, the (A) weighted pressure power level using the results of Clause 9.2.

9.3.2 Record the result of Clause 9.3.1 (See Table 2).

10. DATA PRESENTATION

10.1 Prepare a data summary using the results of Section 9.

10.2 Use Table 2 as an example summary.

10.3 Include the following information on the summary:

10.3.1 Pump description.

10.3.2 Fluid viscosity (cSt, SUS).

10.3.3 Date of test.

10.3.4 Location of test.

10.3.5 Shaft speed.

10.3.6 Discharge pressure.

10.3.7 Inlet pressure.

10.3.8 Inlet temperature.

10.3.9 Type of fluid.

10.3.10 Output flow (for variable displacement units, also state percentage displacements, i.e. 90%, 5%, etc.).

10.3.11 Case pressure.

10.3.12 Compensator setting.

10.3.13 Type of pressure transducer.

10.3.14 Results of test circuit verification.

11. JUSTIFICATION STATEMENT

(To be included following completion of the review process.)

TABLE 2

Example Data Summary

Pump Description ____________________ Fluid ______________________

____________________ Temperature (Inlet) ______ (°C/°F)

Test Location ____________________ Viscosity ________ (cSt, SUS)

Test Date ____________________ Shaft Speed __________ RPM

Discharge Pressure ________ (bar/psig) Output Flow ______ (l/min; USG)

Inlet Pressure ________ $\frac{mm}{in}$ Hg $\frac{bar}{psig}$ % Displacement __________ %

Case Pressure ________ $\frac{mm}{in}$ Hg $\frac{bar}{psig}$ Compensator Setting __________

Type of Pressure Transducer ________ Date Test Circuit Verified ____

____________________ ____________________

Results of Test Circuit Verification ____________________

____

Mean Pressure Level (dB)							
Octave Band Centered On (Hz)	125	250	500	1000	2000	4000	8000

Pressure Power Level ______________ dBA